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Strange, Surprising

Neutrino Physics

The ghostly particles could pave the way to unexplored realms

SPECIAL REPORT

The Future of Medicine 2013

Boosting Self-Healing

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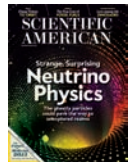
April 2013 Volume 308, Number 4

ON THE COVER



Neutrinos have been puzzling experimental and theoretical physicists for decades. But the oddities of these fundamental particles only add to their intrigue. By studying neutrinos with sensitive detectors, such as the one that inspired the artist's conception on the cover, researchers hope to enter new domains of particle physics. Image by Vault49.

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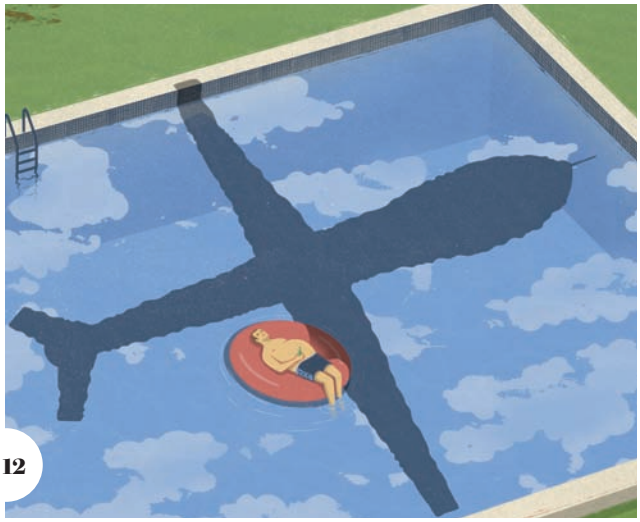
STEPHEN FRINK *Getty Images*



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Go to www.ScientificAmerican.com/apr2013/mars

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A New Agenda

WE PACKED INTO THE ELEGANTLY APPOINTED WHITE House room. The buzzing crowd hushed as President Barack Obama stepped to the lectern. He spoke about the work of some two dozen honorees sitting before us—the winners of the National Medals of Science and Technology, the highest honors bestowed by the U.S. government.

"Thanks to the sacrifices they've made, the chances they've taken—the gallons of coffee they've consumed—we now have batteries that power everything from cell phones to electric cars," he said. "We have a map of the human genome and new ways to produce renewable energy. We're learning to grow organs in the lab and better understand what's happening in our deepest oceans." (Find my blog about the event and the winners at http://goo.gl/O3uFG. One is Robert Langer of M.I.T. and a member of the *Scientific American* Board of Advisers.)

From energy independence to cures for what ails us, science, technology and innovation are our best tools to address the needs of a growing population living in a finite world. The week before the White House ceremony, I was overseas at another event that noted the importance of research: the World Economic Forum (WEF) at Davos, Switzerland, the annual meeting of policy and business leaders. For my part, I moderated, spoke as a panelist, or served as rapporteur (an official commenter) for various sessions.

More important, that meeting marked the start of an exciting initiative: developing a Global Agenda for Science, Technology and Innovation. I was privileged to participate in the small session convened by the WEF to kick off this process, along with my NPG colleague Philip Campbell, editor in chief of *Nature*. The goal is to crystallize focus around key topics and to help bring stakeholders together, improving the flow of information as well as the policy discussions surrounding the application of problem-solving research and technology to global challenges.

At the Annual Meeting of the New Champions to be held in China this September, also called the "Summer Davos," members of related communities will gather to help shape the agenda's basic principles. We hope to present at Davos in 2014. SA

PRESIDENT BARACK OBAMA addresses the winners of the National Medals of Science and Technology.

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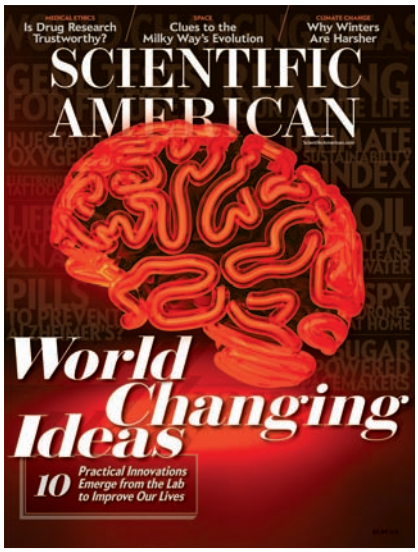

December 2012

POLICING ETHICS

"Is Drug Research Trustworthy?"—Charles Seife's article claiming that scientific institutions and individual scientists are not properly policing conflicts of interest—distorts the National Institutes of Health's interest and role in ensuring objectivity in research. Interactions between researchers and companies are vital for developing drugs, vaccines and medical devices. These partnerships function through collaboration and the need to maintain objectivity. The NIH is committed to ensuring that NIH-funded research is conducted with the highest scientific and ethical standards and that all stakeholders understand and comply with their responsibilities.

The NIH invests significant effort in monitoring conflicts of the researchers it employs, appoints or funds, including the 300,000-plus researchers funded through awards to 2,500 institutions. The revised Public Health Service financial conflicts-of-interest regulations that went into effect in September 2011 strengthen measures to achieve objectivity in NIH-extramural research.

Seife implies that the NIH should directly monitor these NIH-funded researchers rather than the institutions themselves. Institutions, however, know their employees and all their activities and are therefore in the better position to identify and manage a potential conflict. The NIH must rely on the institutions and their researchers to comply with regulations, identify conflicts and enforce the policies to manage them. The NIH reviews the institutional reports and takes action when necessary. Only by engaging all stakeholders in the process can financial conflicts of interest be addressed and public trust in NIH-funded research maintained.

Sally J. Rockey
Deputy Director for Extramural Research
National Institutes of Health

"Intrusion of hidden commercial interests with supposedly independent scientific investigations could be more prevalent outside the U.S."

Jens Christian Jensenius *Århus University*

The trend of allowing the intrusion of hidden commercial interests in supposedly independent scientific investigations in the U.S. could be more prevalent elsewhere. Few other countries have the same openness in administration offered by the U.S. Freedom of Information Act.

Jens Christian Jensenius
Århus University, Denmark

MUTUALLY ASSURED DESTRUCTION

"The Alpinists of Evil," by Michael Shermer [Skeptic], argues that atrocities such as those perpetrated by the Nazis can occur because our morals are modulated by identification with others around us.

I have misgivings about morals being modulated to allow for another kind of atrocity: that caused by nuclear weapons. Some argue that possessing such weapons is permissible under the doctrine of mutually assured destruction (MAD)—in which using them would also result in the attacker's destruction—because doing so may prevent future conflicts. But if a nuclear power is attacked anyway, MAD has failed.

Kurt L. Becker
Durham, N.C.

SHERMER REPLIES: MAD is a game theoretical model in which both sides reach a Nash equilibrium, in which neither side has anything to gain by changing strategies. The concept has worked for 64 years.

MAD requires rational leaders who cherish life as much as we do in the West, and I am thus less confident about its effectiveness than I was before 9/11, given the belief on the part of suicide terrorists that rewards await them in the next life for their actions. Still, I'm optimistic, given the fact that a large number of countries that started nuclear programs eventually stopped.

My moral stand: I support Global Zero and the manifesto entitled "A World Free of Nuclear Weapons," signed, among others, by George P. Shultz and Henry A. Kissinger (not exactly peaceniks). So there's hope.

ANALOG ACTUALITY?

David Tong's "The Unquantum Quantum" speculates that reality is fundamentally analog, not digital. If the history of quantum mechanics is any guide, I would say the answer has to be "both and neither." What could be more discrete than a particle or continuous than a wave? Yet both and neither interpretations are true.

Andy Robertson
via e-mail

TONG REPLIES: The idea that an object is both a particle and a wave is more of a popular slogan than a good description of the math behind quantum mechanics. The wave function is a fundamental concept in quantum mechanics. At a deeper level, the lumpiness of particles emerges from this continuity.

CLIMATE FEEDBACKS

"The Winters of Our Discontent," by Charles H. Greene, discusses how melting Arctic sea ice can cause harsh winters in the U.S. and Europe.

The negative Arctic Oscillation (AO) and negative North Atlantic Oscillation (NAO) climate phenomena are described as associated with conditions allowing cold air to invade south. Yet shouldn't warm air then flow north? If so, is that another positive feedback mechanism contributing to rapid warming in the Arctic?

Ben Harding
Boulder, Colo.

GREENE REPLIES: The polar jet stream has waves in it, and their amplitude tends to be larger during negative AO and NAO conditions. When one part of a wave dips south to bring cold Arctic air to the lower latitudes, another part rises to the north to bring warm air to higher latitudes. Although that warm air may not typically get carried far enough north to directly affect Arctic sea ice melting and the ice-albedo feedback process, there are other processes associated with a wavier jet stream that could contribute to amplification of Arctic warming. The transport of extra water vapor farther north can have the following effects:

1. As an important greenhouse gas, the vapor can absorb outgoing infrared radiation (heat), leading to additional warming of the atmosphere.

2. It can condense to form heat-trapping clouds, which also enhance such warming.

3. Such condensation results in the release of latent heat, further warming the atmosphere.

In addition to these warming effects, a wavier jet stream is associated with the development of blocking patterns, stationary high-pressure systems that stall atmospheric circulation. During some recent summers, enhanced blocking over Greenland has altered wind patterns in a manner favoring the flow of ice out of the Arctic Ocean and into the North Atlantic. This loss of Arctic sea ice will have a similar effect on the ice-albedo feedback process as warming-induced ice melting. Thus, there are good reasons to think that the development of conditions favoring a wavier jet stream could enhance positive feedbacks for even more rapid warming in the Arctic.

CLARIFICATION

In discussing potential conflicts of interest of "employees" of the National Institutes of Health in "Is Drug Research Trustworthy?", Charles Seife refers to special government employees, appointed by the NIH, who serve on its advisory committees.

ERRATUM

"Meat of the Matter," by Ferris Jabr [The Science of Health], incorrectly states that the large intestine grew larger over the course of human evolution; it was the small intestine.

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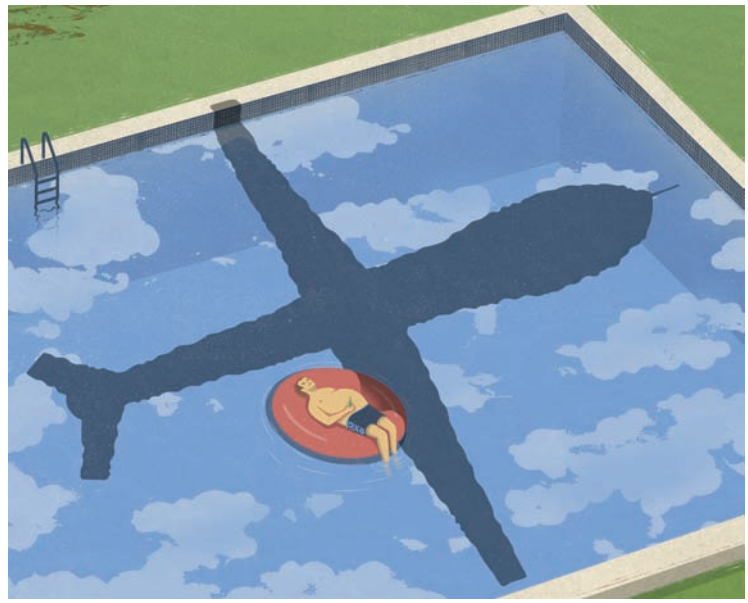
The Spies above Your Backyard

The U.S. government must shield its citizens from the multiplying eyes of surveillance drones



Before the decade is out, there may be thousands more eyes in the sky. Unmanned aerial vehicles, commonly known as drones, are already a staple of modern warfare. Now they are set to take on a much larger role in the U.S.

Congress has directed the Federal Aviation Administration to set rules by 2015 for how drones may be used in domestic airspace. These rules could open up the skies to unmanned vehicles of all types—from large surveillance drones used by the military to insect-size prototypes being developed in university laboratories. The technology promises to be immensely useful. Public safety agencies can use drones to survey wildfires, conduct search-and-rescue operations, or pursue heavily armed suspects. Farmers will use them to survey their fields; energy companies will fly drones over critical machinery.

Still, drones also pose an immense threat to privacy. The proliferation of small, inexpensive aerial vehicles with video downlinks will dramatically alter the cost-benefit ratio of surveillance. No longer will law-enforcement agencies need to consider the expense and risk of operating a helicopter when gathering evidence. Consequently, law-enforcement agencies will have ample opportunity and motivation to deploy drones on open-ended sorties. It is not hard to imagine blanket campaigns that survey entire cities for backyard marijuana plants or even building code violations. Privacy advocates rightly worry that drones, equipped with high-resolution video cameras, infrared detectors and even facial-recognition software, will let snoops into realms that have long been considered private.

The privacy threat does not just come from law enforcement, either. Paparazzi and private detectives will find drones just as easy to use as the cops. Your neighbor is not allowed go into your yard without your permission—will he be able to keep a drone hovering just above it?

Case law paints a hazy picture of how drones could be employed for surveillance. A 1989 Supreme Court decision ruled that police may use helicopters to peer into semiprivate areas—say, the backyard of a home—without first obtaining a warrant. Such speculative reconnaissance, however, has been naturally limited by the costs of helicopter operations. Will the same law apply to unmanned drones, which are not similarly constrained?

A more recent case poses troubling questions about access to the most sacrosanct spaces. In 2001 the Supreme Court ruled that police could not use thermal-imaging technology to gather evidence about the goings-on hidden inside a residence without first obtaining a warrant. The court reasoned that governmental use of "a device that is not in general public use"—a thermal imager—constitutes a search under the Fourth Amendment and therefore requires a judge's approval. Yet if unmanned aerial vehicles become as prevalent as manufacturers hope, one could argue that drones are exempt from that precedent.

Already the FAA has permitted a handful of law-enforcement agencies to operate drones on a short-term basis. The limited regulations accompanying those permits (which, thankfully, preclude attaching any weapons to the drones) are insufficient to protect the privacy of citizens. Perhaps this should not be surprising. The FAA is not in the business of privacy protection. Its primary concern is with the safety of domestic airspace.

No federal agency, in fact, can be held accountable if drones are not used responsibly and in a way that respects the Fourth Amendment. As such, Congress should proactively enact laws that confine domestic drones to reasonable, useful purposes. Several sensible ideas were proposed during the last session of Congress, including a bill that would have outlawed drone spying without a warrant and instituted important transparency and accountability measures for their use. But that bill failed to make it out of a subcommittee. The present Congress must be more active than its predecessor in heading off this clear and impending threat to personal privacy. SA

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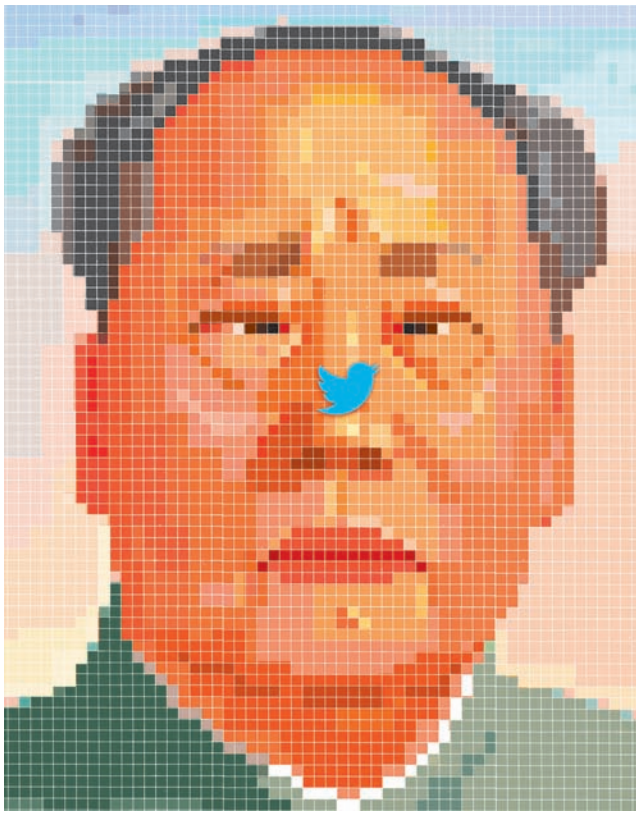
Illustration by Francesco Bongiorni

Commentary on science in the news from the experts

Guobin Yang is an associate professor at the University of Pennsylvania and is author of *The Power of the Internet in China: Citizen Activism Online* (Columbia University Press, 2009).



The People's Standoff

China's Twitter generation squares off against the "Great Firewall"

Barely two months after Xi Jinping was named China's new leader, the Twitter generation seemed to be gaining the upper hand over the nation's status quo regime. Ham-handed censors rewrote an editorial in the newspaper *Southern Weekend* without notifying the editors—and even managed to add a glaring historical error. Censorship is routine in China, especially for liberal periodicals such as *Southern Weekend,* but this time the editors went ballistic. They cried foul on Sina Weibo, the country's popular microblogging platform, and wrote an open letter calling for the removal of the provincial propaganda chief. Voices of Netizens joined in support with signature petitions online. Protesters appeared in the streets of Guangzhou.

The event smacked of the Arab Spring, when authoritarian regimes in the Middle East and northern Africa fell to rebellions that were in part inspired by social media. Indeed, the Guangzhou protesters managed to obtain concessions from the authorities, who reportedly granted the newspaper more autonomy in its future operations. The incident marks a new degree of openness in the way state authorities deal with online and street protesters. Some observers have said that it may signal more radical political change to come. That is not likely, however.

To be sure, for more than a decade China's ruling Communist Party has been under pressure from the rise of information technologies—the Internet, blogs, social media. Westerners tend to see what is going on in China as a battle of rebels against an autocratic state. Yet it would be more accurate to think of China's social media revolution as a Tai Chi–style contest—a long entanglement of slow advances and tactical retreats whose result is not determined by a few strong blows. State authorities and contentious citizens are engaged as if in a half-choreographed war dance, constantly shifting their positions to avoid or absorb their opponent's force while awaiting the opportune moment to attack.

The technology that gives citizens more power to interact and organize has also given the central and provincial governments a great deal of power to obfuscate and confuse. To contain Internet dissent and protest, China aggressively censors Web sites. New regulations or crackdowns are often implemented after new outbursts of online protest. This was the case when the first policy to regulate electronic bulletin boards took effect in 2000. When crude sanctions failed to curb online dissent, the government turned to a more subtle measure: sprinkling anonymous Internet commentators to promote the party line throughout the blogging community. According to a report issued by the official news Web site People's Daily Online, more than 60,000 government accounts were active on Sina Weibo alone by the end of 2012. With its enormous resources, the government can have its Web sites pour out large volumes of information that serve to inundate dissent.

Netizens and activists fight back by being creative. To avoid keyword filtering, they discuss sensitive issues by using historical allusions, word games and similar methods. Some gain access to blocked Web sites such as Twitter by using software and proxy servers. They adapt, compromise, retreat or push back by carefully gauging the circumstances and seizing opportunities. Their numbers are rising. In December 2010 China had 63 million microbloggers out of 457 million Internet users. Today more than 300 million Internet users are microblogging.

This rising tide of online dissent has in recent years compelled the state to give more recognition to the legitimacy of opinion that is expressed online. Yet the *Southern Weekend* brouhaha exemplifies more of a give-and-take between rebels and authorities than a simmering revolution about to boil over. Sina Weibo quietly tightened its surveillance and filtering. Police showed up to the protests in Guangzhou, but there was no violence, and the affair ended peacefully. No party official got the sack. SA

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Illustration by Doug Chayka

Shine on: Star-making region in the Large Magellanic Cloud

ASTRONOMY

Unraveling a Magellanic Mystery

New Hubble data shed light on how the Milky Way's two brightest satellite galaxies maintain their youthful glow

Our galaxy, the Milky Way, is more than just a giant spiral harboring hundreds of billions of stars. It's also the hub of a gargantuan empire that stretches over more than a million light-years and rules some two dozen lesser galaxies, which revolve around it the way moons orbit a giant planet.

Of all our galaxy's many satellites, none compares to the Magellanic Clouds—a pair of bold and beautiful galaxies far more lively and lustrous than any other in the Milky Way's retinue. Visible in the southern sky as fragments of glowing mist, this galactic duo poses something of a mystery to astronomers. The Milky Way's gravity has robbed all its other satellites of the gas they need to make stars, so how have the Large and Small Magellanic Clouds remained so bright and bountiful, filled with brilliant young stars and the gas and dust that create them?

Evidence is mounting that the Magellanic Clouds are so healthy because until recently they have avoided the Milky Way and its gas-grabbing tactics. Seven years ago Nitya Kallivayalil, an astronomer now at Yale University, and her colleagues reported Hubble Space Telescope observations showing that their orbit was much more enormous than previously thought. Prior to Kallivayalil's work, astronomers thought the Magellanic Clouds orbited our galaxy every one or two billion years. Now it seems they require at least four billion years to fully revolve around it—and possibly much longer. Her latest Hubble data, published in February, yield a more precise path for the pair and strengthen her initial discovery, suggesting the Magellanic Clouds are most likely passing us for the first time, which would explain their youthful glow.

Yet even the clouds' splendor will someday fade. Gurtina Besla, an astronomer at Columbia University, says tides from the Large Magellanic Cloud extract stars and gas from its smaller sibling, whose fate is bleak: "I think the Small Magellanic Cloud is on its way to becoming a dwarf spheroidal"—a ghostly, gas-poor object like the Milky Way's other satellites. Fortunately, that will take a long time. By venturing past the Milky Way only now, both galaxies still bear abundant gas to forge brilliant new stars that will deck southern skies for eons to come.

—Ken Croswell

COURTESY OF NASA/CXC/PSU/L. TOWNSLEY ET AL. (*x-ray*); NASA/JPL/PSU/L. TOWNSLEY ET AL. (*infrared*)

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MEDICINE

Medieval and Modern

New studies show how maggots clean wounds and help them heal

From ancient times until the advent of antibiotics, physicians used maggots to help clean injuries and prevent infection. Because the maggots feed solely on dead flesh, doctors did not have to worry about bugs feasting on healthy tissue. The arrival of antibiotics relegated medical maggots to an artifact of an earlier era.

Widespread antibiotic resistance, however, rekindled interest in the use of medical maggots, and in 2004 the FDA approved them as a valid "medical device." Today maggot providers raise the larvae from sterilized fly eggs and place them in tea bag–like packages that physicians apply directly to wounds. (The packages prevent the maggots from crawling off and completing their maturation into adult flies.) As more physicians have turned to the insects to treat wounds, scientists have uncovered the two-pronged process by which maggots work their magic.

One study published last year in the *Archives of Dermatology* showed that maggots placed on surgical incisions helped to clear more dead tissue from the sites than surgical debridement, the current standard of care in which doctors use a scalpel or scissors. "Maggot debridement takes out all the dead and infected tissue, which is necessary for the wound to close," says lead author Anne Dompmartin-Blanchère, a dermatologist at the University Hospital Center of Caen in France. Surgical debridement is often lengthy and painful, something that maggot therapy eliminates, she adds.

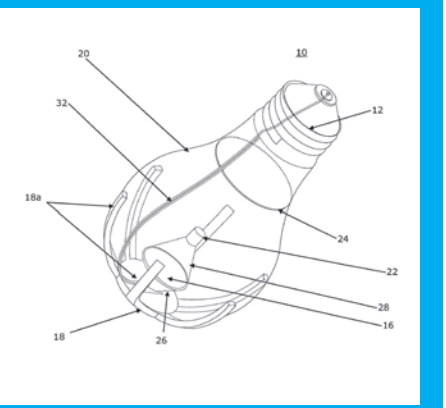
A separate study published late last year in *Wound Regeneration and Repair* by Gwendolyn Cazander of Leiden University Medical Center in the Netherlands and her colleagues found that secretions from the maggots modulate the complement response, a part of the immune system that reacts to invading pathogens and is crucial to clearing infections. Some complement activation is necessary, but too much complement leads to chronic inflammation, which can keep injuries open and vulnerable to infection. Maggot secretions turned down complement activity in blood samples from healthy adults by inhibiting the production of several important complement proteins, and, the researchers found, reducing this overactive immune response speeds up healing. "About 50 to 80 percent of the wounds we see can be healed with maggots," Cazander concludes.

Maggot therapy might sound medieval, but modern medicine seems to show that it works. —*Carrie Arnold*

PATENT WATCH

Solid-state light source lightbulb: Light-emitting-diode (LED) bulbs produce more light with less energy than incandescents, could potentially claim a lamp life much longer than 10 years, and, unlike compact fluorescents, are free of mercury. But they have other drawbacks. To obtain that lengthy life, LED devices need to stay relatively cool. And to successfully replace current bulbs, LEDs would need to broadcast their rays widely, yet many currently on the market give off light unidirectionally, like a flashlight.

Nadarajah Narendran, a professor and director of research at the Lighting Research Center at Rensselaer Polytechnic Institute, and his co-inventors came up with an LED bulb that addresses both problems in Patent no. 8,292,468. "Heat is one of the problems with LEDs," Narendran says. "If you don't create it in the right way, you may not have the long life." Other LEDs have large metal heat sinks that dissipate heat at the base or back of the bulb. That placement can create a shadow and the flashlight effect, he says. His device inverts the typical design by putting the LED source and the metal heat sink at the front of the bulb, where there is more exposure to surrounding air and cooling is more efficient. The bulb also has interior features that reflect and refract to produce light distribution that mimics an incandescent lamp. The result: a long-lived bulb with familiar aesthetics. "The lighting industry is in the process of a transformation," Narendran says. "In many cases, the look will not change—it will look like a lightbulb—but what's inside will change." —*Marissa Fessenden*



PHILIPPE PSAILA *Science Source (top)*; COURTESY OF U.S. PATENT AND TRADEMARK OFFICE (*bottom*)

HEALTH

"Doc, I'm off My Diet. LOL"

Mobile health care may be falling short

The promise of using text messages, video or smartphone apps to improve health care has attracted a lot of attention and dollars. Yet mobile health, also known as mHealth, is still in its infancy, and a pair of new analyses shows that it has garnered mixed results. Of 75 controlled trials in which patients used mobile technology to manage a disease or adopt healthier behaviors, only three showed reliable signs of success, according to a review article published in January in *PLOS Medicine.*

In an accompanying review, the same authors looked at the use of mobile technology to improve health care delivery, such as using text messages to remind patients about appointments, and found that 11 of 42 trials had positive results.

Physician Rahul Chakrabarti of the University of Melbourne in Australia, co-editor in chief of the *Journal of Mobile Technology in Medicine,* calls the reviews the most comprehensive meta-analysis of mHealth evidence to date.

The limitations of today's mHealth treatments should not discourage researchers, says epidemiologist Caroline Free of the London School of Hygiene and Tropical Medicine, who led the analysis. People can learn from interventions that did work. For instance, receiving text messages helped smokers quit in one trial that verified its results with biochemical tests. In the only successful patient-intervention trial in the developing world, in Kenya, text message reminders to take antiretroviral drugs helped to reduce HIV virus counts.

The bad news is that most trials had weak designs, with many failing to randomize participants in the control group and the experimental group. Others relied on participants to self-report the results, even though such methods can be unreliable. Most trials also neglected the developing world, where mobile phones have the most potential to improve access to health care.

Chakrabarti, who was not involved in the research, says that the studies show "there is a clear need for improved methodology."

—Lucas Laursen

SOCIOLOGY

Of Lust and Lysol

Men who do more housework have less sex

Conventional wisdom suggests that women are drawn to men who help out around the house. Yet new research indicates that some divisions of labor may be sexier than others. A February paper in the *American Sociological Review* reported that married couples in which men take on a greater share of the dishes, laundry and other traditionally female chores had sex less often than average, which in this study was about five times a month. Yet couples in which men confined themselves largely to traditionally male chores such as yard work enjoyed sex more frequently than average. Taken to the extreme, men who performed all the traditionally female chores would have had sex 1.6 times less often than men who did none of them. The study authors, from the Juan March Institute in Madrid and the University of Washington, arrived at the correlation by crunching data from the National Survey of Families and Households (NFSH), which gathered survey information from 4,500 U.S. married couples. The researchers ruled out any kind of coercion on the part of the "manly" chore-performing husbands by looking at data from the same survey on sexual satisfaction: they found that women from households with more traditional divisions of labor felt no less happy with their sex lives than women in more gender-neutral ones.

The study has its skeptics. Its data were gathered between 1992 and 1994, making demographer Sharon Sassler of Cornell University wonder about their relevance today. "In the past two decades," she says, "who gets married has changed considerably." Today most couples cohabit before marrying, and a large proportion of the women in those couples, Sassler argues, are not satisfied doing a disproportionate share of so-called women's housework. According to Sassler, frequently those couples do not marry, making the set of couples who would qualify for the NSFH today profoundly different from the set in 1992.

Study co-author Julie Brines, a sociologist at the University of Washington, says men and women have deep-seated ideas about what is masculine and feminine. Displays of masculinity may evoke feminine displays in women, which activates or intensifies sexual charge. Put the man on a rider mower, in other words, and boom—fireworks. Stand him at a sudsy sink, and it's a probable no go. *—Rebecca Coffey*

ISTOCKPHOTO

Illustrations by Thomas Fuchs

SCIENTIST IN THE FIELD

Extremely High and Incredibly Cold

A wildlife biologist ventures to the Tibetan plateau to count wild yaks

There are around 14 million domestic yaks in the world, but nobody knows how many wild yaks there are. They're a vulnerable species. The Tibetan Himalayan region, their home, has tens of thousands of glaciers, and as the snow and the ice melt, we're not sure what it's going to do to yaks. Our expedition to the Tibetan plateau last November and December was to get a better handle on where we can find yaks and start to figure out how they're going to respond to changes. We picked that time of year because everything is frozen solid, and we can drive across lakes and marshes. Temperatures get pretty cold: it's an interesting challenge to get out of a sleeping bag when it's –20 degrees Fahrenheit.

We did a snapshot survey in the northeastern corner of the Tibetan plateau, where we counted about 990 yaks. Poachers have targeted wild yaks for their meat and hide up until the past half a century. Our Chinese collaborators have done a great job with antipoaching patrols, and it appears that the yak numbers are coming back, but we don't have good measures of the trends.

Wild yaks used to occur down to elevations around 10,000 feet, whereas now they are restricted to elevations around 14,500 feet—and up to 17,500 feet. It's likely the reason that they don't occur at such elevations now is contact with people [who have encroached on their territory] rather than temperature intolerance.

When I think about these places at the limits of life, I think about the future. Ultimately, what can we do to ensure the persistence of wild yaks? What kind of actions do we need to take that also account for human livelihoods in that area? I work with colleagues, government employees and herders because they care just as much as I do. If we don't address the concerns of people, we're never going to conserve the species.

—As told to Marissa Fessenden

PROFILE

NAME
Joel Berger

TITLE
Wildlife biologist, University of Montana and Wildlife Conservation Society

LOCATION
Missoula, Mont., and Bronx, N.Y.

GETTY IMAGES

ENERGY

Better, Cheaper, Smaller

New nanowire solar cells achieve record efficiency

Here's how to make a powerful solar cell from nanowires: First, arrange microscopic flecks of gold on a semiconductor background. Using the gold as a foundation, build wires roughly 1.5 micron tall out of chemically tweaked compounds of indium and phosphorus using heat and vacuum pressure. Keep the nanowires in line by etching them clean with hydrochloric acid and confine their diameter to 180 nanometers. (A nanometer is one billionth of a meter.) Exposed to the sun, such a nanowire solar cell can turn nearly 14 percent of the incoming light into electricity—a new record for nanowire photovoltaics that opens up more possibilities for cheap and effective solar power.

According to research published online in *Science*—and validated at Germany's Fraunhofer Institute for Solar Energy Systems—this novel nanowire configuration delivered nearly as much electricity as thin-film versions, even though the nanowires covered only 12 percent of the device's surface. That achievement suggests such nanowire cells could prove cheaper—and more powerful—if the process could be industrialized, argues physicist Magnus Borgström of Lund University in Sweden, who led the effort.

The key will lie in developing even finer control of the nanowires as they grow and in chemically tweaking the constituent compounds. Borgström also hopes to simplify the production process by building the nanowires using simple heat and evaporation techniques, which should help further bring down the cost. *—David Biello*

COMMENT AT ScientificAmerican.com/apr2013

Best of the Blogs

ENTOMOLOGY

Dung Beetles Follow the Stars

The excrement-rolling bugs navigate by the light of the Milky Way

The humble dung beetle makes its living rolling big balls of excrement to feed its offspring and itself. But this lowly occupation doesn't mean the insect doesn't have its eye on the skies—even when the sun goes down.

Recent research has shown that a species of ball-rolling dung beetles (*Scarabaeus satyrus*) uses strong light cues from the sun and moon to keep traveling in a straight path. Yet researchers at Sweden's Lund University and South Africa's University of the Witswatersrand noticed that even on clear, moonless nights, many dung beetles still managed to steer a straight path.

To see if the sky was serving as a guide, the researchers, who published their study online January 24 in *Current Biology*, designed specially crafted cardboard caps for their subjects. On a starry evening, they released capped beetles with their dung balls from a central spot in Vryburg, South Africa. As a test, other beetles were left uncapped, and a third group received transparent plastic caps. The beetles without caps and those with clear caps had standard, relatively straight paths: because competition among dung beetles for food is fierce, the insects prefer to flee in a straight line as soon as they roll their dung into a ball. Those with the obstructed views meandered far afield, however, and had much longer, inefficient trails.

To make sure that the stars were the only guiding landmarks, the researchers designed several more experiments. In one, they transported their beetles to the Johannesburg Planetarium. A close approximation of the night sky, including individual stars and the Milky Way, led to the more exacting navigation. If shown just the Milky Way, as a diffuse stripe of light, the beetles still made good time. But if the researchers took the Milky Way out of the picture and gave the beetles 18 bright "stars" to navigate by, they did not stick to their direct paths and took more than 50 percent longer to reach their destination.

"This clearly shows that the beetles do not orientate to a single bright 'lodestar' but rather to the band of light that represents the Milky Way," the researchers note. Their findings may represent the first convincing demonstration of the use of the Milky Way for orientation in the animal kingdom.

—Katherine Harmon

Adapted from Observations at blogs.ScientificAmerican.com/observations

EVOLUTION

Scrappy Pets

Adaptation to a starchy diet may have been key to the domestication of dogs and cats

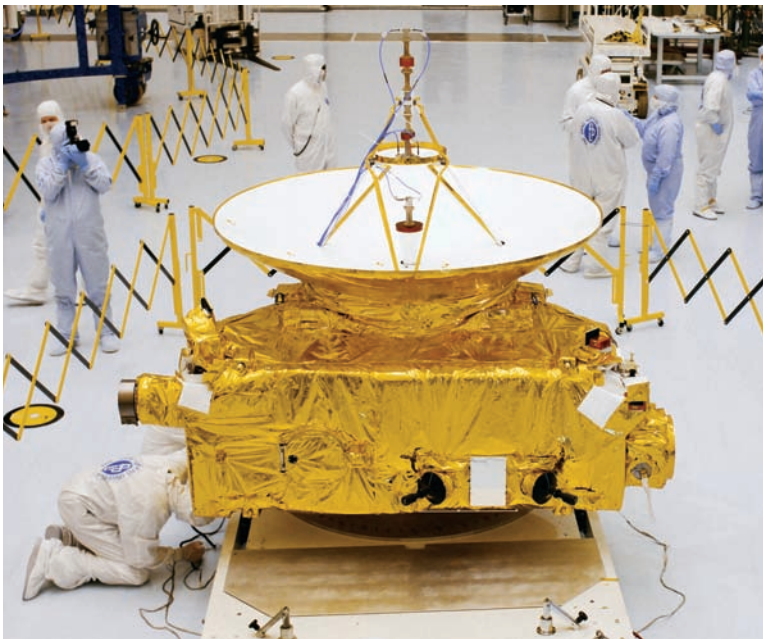
Scientists have two theories for how dogs became man's best friend. One holds that people captured wolf pups and tamed them for their hunting and guarding abilities. The other, more popular explanation proposes that the advent of agriculture and the attendant development of human settlements in the Middle East around 10,000 years ago created scavenging opportunities for animals bold enough to exploit them and that wolves themselves thus initiated domestication. The new findings, published online January 23 in *Nature*, support this latter view and offer insights into how canine ancestors were able to take advantage of this novel resource. (*Scientific American* is part of Nature Publishing Group.)

Erik Axelsson of Uppsala University in Sweden and his colleagues analyzed DNA from 12 wolves and 60 dogs that represent 14 diverse breeds, looking for regions of the dog genome that evolved under selection pressure during domestication. Intriguingly, genes involved in the metabolism of starch showed up among the targets, along with genes that may have brought about behavioral changes such as reduced aggression and improved social-cognitive skills. In fact, the study revealed that during the domestication of dogs, selection acted on genes involved in all three stages of starch digestion, promoting mutations that facilitated the transition from a meat-centric diet to one heavy on starch.

ELIZABETH ALDRIDGE *Getty Images*

Previous studies have shown that cats, too, may have domesticated themselves by dining on human leftovers. Although house cats have only a limited ability to metabolize carbohydrates, including starch, they possess a longer intestine than their wild counterparts, presumably to help digest the lower-quality sustenance they get from trash heaps compared with the all-meat diet they would be living on in the wild, according to geneticist Carlos Driscoll of the National Institutes of Health. In other words, begging for table scraps has been a long dog and cat tradition. *—Kate Wong*

Adapted from Observations at blogs.ScientificAmerican.com/observations



New Horizons probe in 2006

ASTROPHYSICS

Wanted: New Worlds beyond Pluto

Scientists work to keep an intrepid spacecraft busy

In July 2015 the New Horizons spacecraft will venture past the farthest worlds NASA has ever visited, mysterious Pluto and its many moons. As if that achievement were not impressive enough, scientists are already plotting New Horizons's next move, seeking uncharted worlds beyond Pluto for the craft to study close-up.

Pluto is either the largest or second-largest member of the Edgeworth-Kuiper belt, a region boasting 1,600 objects that astronomers have discovered and tracked. But New Horizons will not pass close to any of them. Because a good spacecraft is a terrible thing to waste, astronomers are looking for new heavenly bodies for the spacecraft to observe. "We would be happy to find one," says Alex Parker, an astronomer at the Harvard-Smithsonian Center for Astrophysics. "And we would be ecstatic to find two."

The search uses telescopes in Hawaii and Chile. Astronomers compare images taken on different nights and identify objects that move. So far the project has netted dozens of small worlds, three of which will come within 10 million to 20 million miles of New Horizons in 2018. From that distance, the spacecraft can search for moons, which reveal the main body's mass by responding to its gravitational pull. But Parker wants more—worlds that the probe can approach from a distance of just a few thousand miles. Then it can scrutinize them the same way it will Pluto.

Unfortunately, such objects are now traveling through the worst constellation in which to find unknown worlds: starry Sagittarius, which harbors the center of our Milky Way. "It's very difficult to see these faint moving objects in front of thousands and thousands of background stars," Parker says. Still, given the new worlds the search has already found, he is optimistic it will keep New Horizons employed long after it passes Pluto. —*Ken Croswell*

SCOTT ANDREWS *Getty Images*

MEDICINE

Traces of Cancer

A promising technique may lead to rapid, accurate and less invasive diagnoses

Fragments of RNA that cells eject in fatty droplets may point the way to a new era of cancer diagnosis, potentially reducing the need for invasive tests. Cancer tumor cells shed so-called exosomes, fatty droplets that contain proteins and RNA fragments, into cerebral spinal fluid, blood and urine. Within these exosomes is genetic information that scientists can analyze to determine the cancer's molecular composition and state of progression. Researchers at Massachusetts General Hospital discovered in 2008 that exosomes preserve the genetic information of their parent cells. But they have not seen widespread clinical testing as a means of cancer diagnosis until now.

"This is really a new strategy," says Harvard Medical School neurologist Fred Hochberg, one of the researchers in a clinical study using new exosomal diagnostic tests to identify a genetic mutation found exclusively in glioma, the most common form of brain cancer. Hochberg and his colleagues plan to present preliminary results from the pilot study, which involves 18 U.S. hospitals, in April at a symposium in Boston.

When treating many forms of cancer, surgeons are able to biopsy tumors to diagnose and monitor the state of the disease. For brain cancers such as glioma, however, multiple biopsies can be life-threatening. Bob Carter, head of the study and of neurosurgery at the University of California, San Diego, Medical Center, says study researchers separate exosomes from biofluids with a diagnostic kit and then extract the relevant genomic information. Once the specific cancer mutation is identified, clinicians periodically draw additional biofluids to monitor the mutation levels and determine whether a patient is responding to therapy.

"What we are trying to finalize are the sensitivity and specificity of the test," he says. Exosome diagnostics could also be used in conjunction with current methods, such as prostate-specific antigen (PSA) tests for prostate cancer. The combination would help physicians determine the nature of a tumor and what type of treatment it warrants. "If someone has a high PSA and also has biomarkers that are positive in exosomes, that would be a great test," says Sudhir Srivastava, head of the National Cancer Institute's Cancer Biomarkers Research Group. —*William Ferguson*

TECHNOLOGY

Twitching to Talk

A breakthrough may speed communication

Stephen Hawking has long relied on technology to help him connect with the outside world. For the past decade the renowned physicist, who has battled a degenerative motor neuron disease for half a century, has used a voluntary twitch of his cheek muscle to compose words and sentences one letter at a time. Each tweak stops a cursor that continuously scans text on a screen. But in recent years his condition has deteriorated, and he now communicates at the rate of just one word per minute. In late 2011 Hawking contacted Intel to ask if the company could help.

Intel chief technology officer Justin Rattner noted at the International Consumer Electronics Show in January that the company has built an improved word predictor and is exploring the use of facial-recognition software to speed communication. This work is part of Intel's broader research into devices that can help the elderly and disabled. The key is "context awareness," technology that allows gadgets to anticipate users' needs, such as letting them know about appointment times and reminding them to carry enough cash when running errands.

Intel's plan requires a combination of hardware sensors—camera, accelerometer, microphone, thermometer and others—with software that can check one's personal calendar, social networks and Internet browsing habits, to name a few.

Said Rattner: "We'll be emotionally connected with our devices in a few years." —*Larry Greenemeier*

DIMITRIOS KAMBOURIS *Getty Images*

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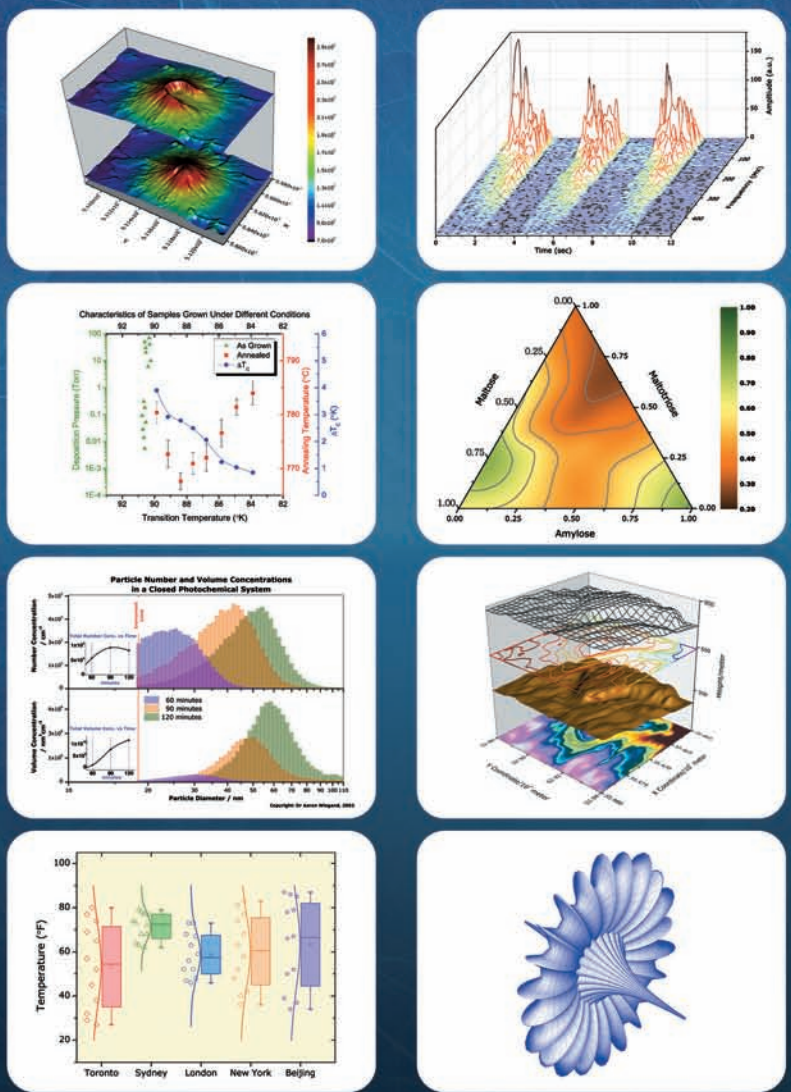

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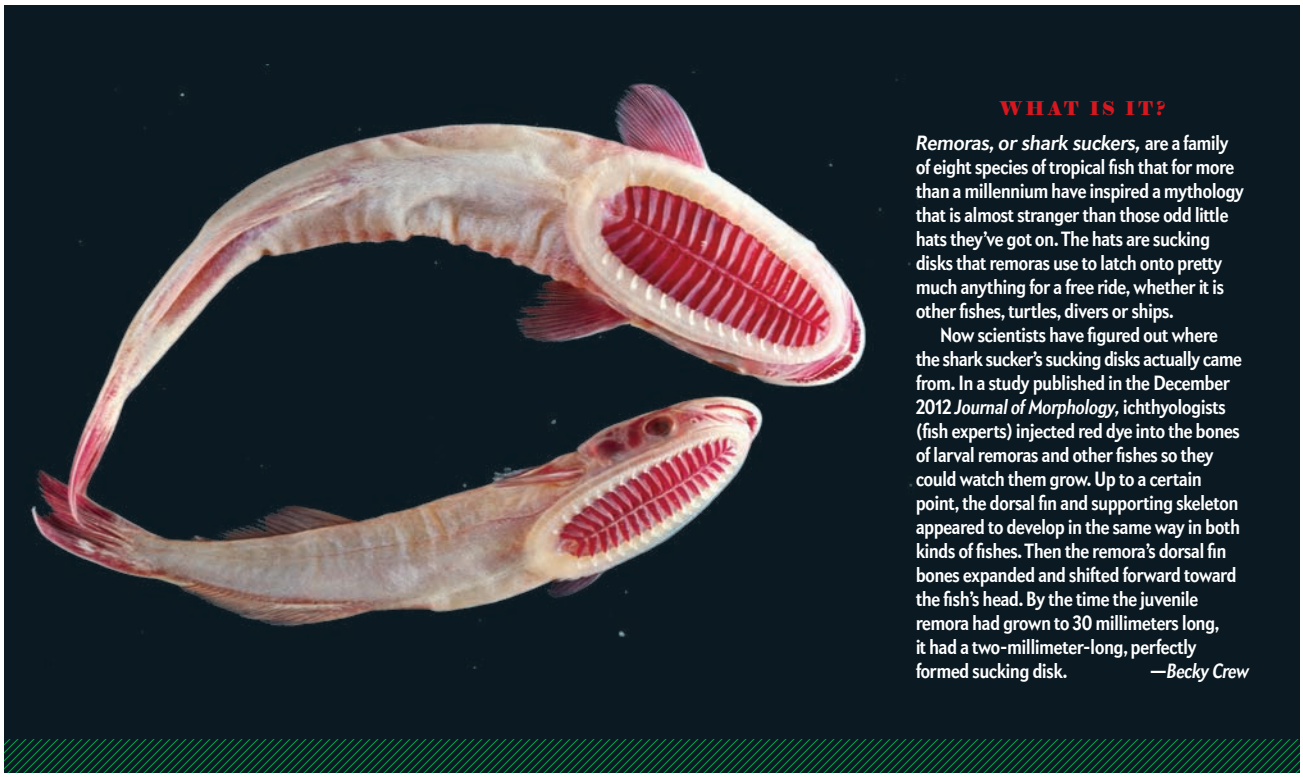


NORBERT WU *Minden Pictures*

WHAT IS IT?

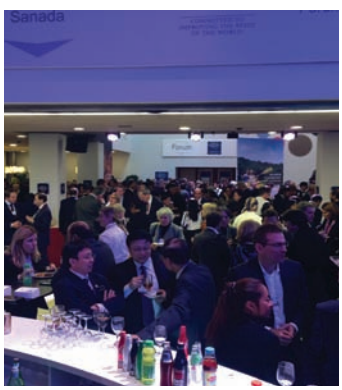
Remoras, or shark suckers, are a family of eight species of tropical fish that for more than a millennium have inspired a mythology that is almost stranger than those odd little hats they've got on. The hats are sucking disks that remoras use to latch onto pretty much anything for a free ride, whether it is other fishes, turtles, divers or ships.

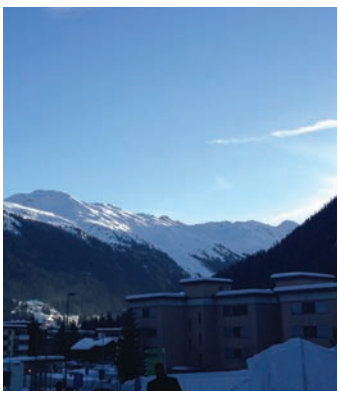
Now scientists have figured out where the shark sucker's sucking disks actually came from. In a study published in the December 2012 *Journal of Morphology,* ichthyologists (fish experts) injected red dye into the bones of larval remoras and other fishes so they could watch them grow. Up to a certain point, the dorsal fin and supporting skeleton appeared to develop in the same way in both kinds of fishes. Then the remora's dorsal fin bones expanded and shifted forward toward the fish's head. By the time the juvenile remora had grown to 30 millimeters long, it had a two-millimeter-long, perfectly formed sucking disk. —*Becky Crew*

PROMOTION

The Agenda Setters

Bringing Science to Life





World Economic Forum

Davos, Switzerland | January 23–27, 2013

SCIENTIFIC AMERICAN **Editor in Chief Mariette DiChristina** participated in the World Economic Forum's annual meeting which is committed to improving the state of the world. Among the other participants with whom she met in Davos was **Australian Minister for Foreign Affairs Bob Carr**.

NEUROSCIENCE

Good Vibrations

Humans may use quantum vibration to smell

How does the sense of smell work? Today two competing camps of scientists are at war over this very question. And the more controversial theory has received important new experimental confirmation.

At issue is whether our noses use delicate quantum mechanisms for sensing the vibrations of odor molecules, aka odorants. Spectroscopes in chemistry and forensics laboratories do this all the time; the machines bounce infrared light off mystery materials to reveal the telltale vibrations that the light provokes. Olfaction might do the same by using tiny currents of electrons instead of infrared photons.

This explanation runs counter to the predominant theory of smell today, which holds that the millions of different odorants in the world are like puzzle pieces. Noses contain scores of different kinds of receptors that each prefer to bind with specific types of pieces. A receptor that is set to bind to a molecule called limonene, for example, sends a signal to the brain when it finds that compound, which is one of the cues behind the smell of citrus.

Yet here's a twist: many odorant molecules contain one or more hydrogen atoms. And hydrogen comes in three forms, each chemically very similar to the others. But those different isotopes of hydrogen have different masses and strongly affect how a molecule vibrates. So deuterium, whose nucleus contains both a proton and a neutron (twice as heavy as the most common kind of hydrogen, which has just a proton), might help scientists discriminate between the proposed vibration and standard chemical binding theories of olfaction.

According to research published in January in *PLOS ONE*, human noses can sniff out the presence of deuterium in some odorants. Specifically, experimenters found that regular musk molecules smell different from ones that contain deuterium. Study co-author Luca Turin of the Alexander Fleming Biomedical Sciences Research Center in Greece says the finding represents a victory for the vibration theory.

Others disagree. Eric Block, professor of chemistry at the University at Albany, S.U.N.Y., points to previous work showing that human noses cannot smell the presence of deuterium in acetophenone (which smells sweet to humans). Turin proposes an explanation for the failure: deuterated acetophenone has relatively few deuteriums in it and thus may generate a vibrational signal that is too weak for humans to detect. Block says Turin can't have it both ways, and so the controversy continues. —*Mark Anderson*

"Braveness in the face of tofu a plus."

(from Science Connection member profiles)

"Looking for someone to write home to Mother about."

"Can fix most things, given enough time & especially if it isn't worth repairing in the first place."

"Factor polynomials for relaxation, want to move on to sequences."

"Jewish, please. Not important if religious, but I can't keep explaining the jokes."

"Attempts understanding women but mostly in awe..."

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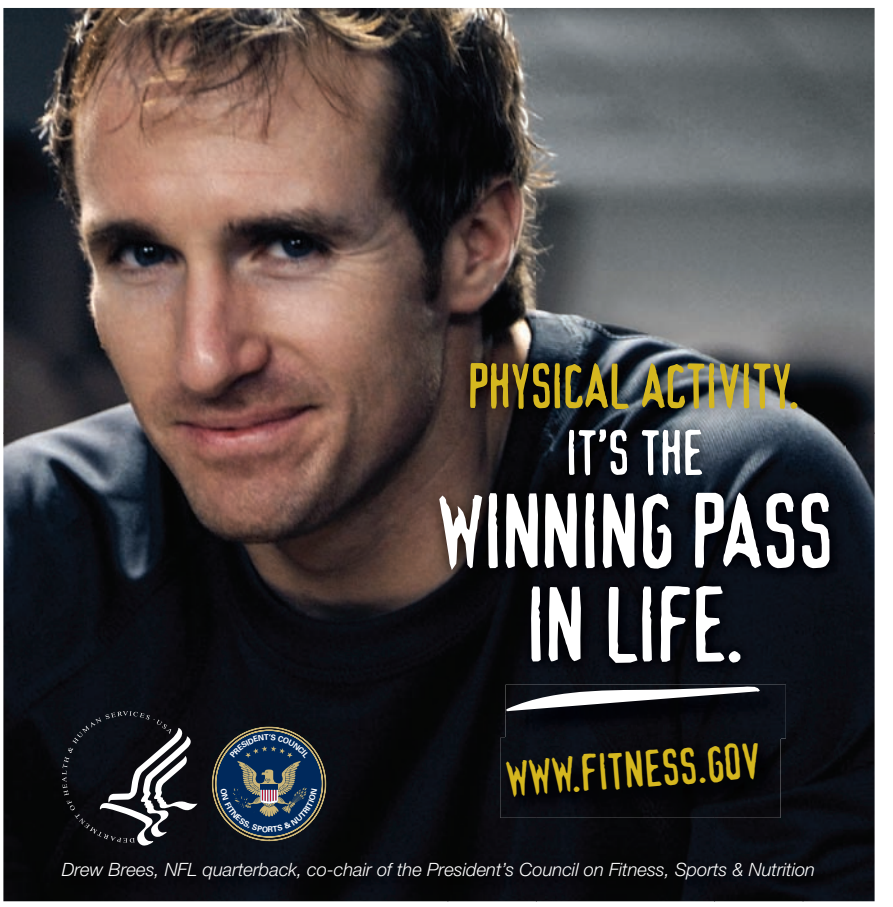

Maryn McKenna is a journalist, a blogger and author of two books about public health. She writes about infectious diseases, global health and food policy.

Shock to the System

During sepsis, the body attacks itself. Researchers are working on new ways to fight back

Sepsis is a serious and often deadly illness, yet it remains an unfamiliar threat to most of the general public, as well as one of the most difficult diseases for doctors to diagnose and treat. The condition, which begins with an aggressive immune system reaction to an infection, kills 18 million people around the world every year, including around 260,000 in the U.S. By many estimates, sepsis—and its most severe form, septic shock—is the leading cause of death for intensive care patients in the U.S. and the 10th most common cause of death for everyone else in the country. Yet only one in five Americans recognizes the term, according to a 2011 study commissioned by the nonprofit group Sepsis Alliance, and of those survey participants who had heard of sepsis, most could not define it.

Even physicians, who learn about sepsis in medical school, often miss its early signs because they mimic other disorders and because the illness progresses so rapidly from what looks like a mild infection to a life-threatening situation. As a result of these difficulties, doctors are often late to launch the necessary interventions, such as antibiotics to obliterate the infection, drugs to counteract a perilous drop in blood pressure, and a mechanical ventilator to raise dangerously low oxygen levels.

"The timing of antibiotics is a critical determinant for whether someone lives or dies," says James O'Brien, who is medical director of quality and patient safety at Riverside Methodist Hospital in Columbus, Ohio, and serves as an adviser to Sepsis Alliance. But some of the most compelling data out there, he says, shows that only 50 percent of patients with septic shock get appropriate antibiotics within six hours of first being seen by a health professional. "If we had a similar record with getting heart attack patients to the catheterization lab, there would be an uproar," he adds.

To further complicate the picture, better treatments have been slow in coming. Some are on the horizon—such as an experimental blood test and filtration therapy—but failure of four potential antisepsis drugs in the past two years has discouraged researchers and advocates alike. Carl Flatley, a retired dentist, founded Sepsis Alliance after his daughter died of the syndrome in 2002. "In the 10 years since, we have lost 2.5 million people to this [in the U.S.], and it could take another 10 years before we have something that works," he says. "We need to move faster."

CHEMICAL CASCADE

SEPSIS BEGINS INNOCUOUSLY ENOUGH when the immune system performs its usual task of recognizing invading bacteria, viruses or fungi. Immune cells release signaling proteins called cytokines to stimulate one another and overcome the invaders—but for poorly understood reasons, the immune cells release far more cytokines and other inflammatory molecules than is typical. All the extra immune molecules surging through the bloodstream have the inadvertent effect of making blood vessels slack and permeable, reducing blood pressure and allowing the fluid component of the blood to seep into surrounding tissues. The blood components left behind clot in the smallest vessels, preventing oxygen from reaching major organs. At this point, someone with sepsis has transitioned from the earliest stage of the disease, known as systemic inflammatory response syndrome, to the later stages of severe sepsis and septic shock. Confusion sets in, the heart's electrical activity becomes erratic, the kidneys and other organs fail, and blood pressure cannot be raised even with large amounts of intravenous fluids and drugs.

Because the immune system's reaction is responsible for

Illustration by Shannon Freshwater

the destructive progression of sepsis, researchers have tried using various drugs to interrupt the chemical cascade that triggers inflammation and clotting. Recent attempts have been disappointing.

In January 2011 the highly anticipated drug eritoran, made by Tokyo-based Eisai, was withdrawn after clinical trials showed no benefit in comparison with a placebo in preventing sepsis deaths. By October of that year the drug that eritoran had been intended to compete with—Xigris, made by Eli Lilly—was withdrawn from sale 10 years after being licensed by the U.S. Food and Drug Administration because mandatory postmarketing studies showed no benefit to patients. In February 2012 Agennix in Munich, Germany, halted studies that applied its existing cancer drug, talactoferrin, to sepsis after the number of deaths among patients receiving it in rigorous clinical trials turned out to be greater than the number of deaths among placebo recipients. Later that year, in August, research into the new drug CytoFab was canceled by partners AstraZeneca and BTG after an early trial showed no effect greater than a placebo.

All those drugs were predicted to be billion-dollar blockbusters if they had proved effective against sepsis, but instead they cost their creators millions in foregone research and canceled trials. As a result, "I think the big companies have given up," says Richard P. Wenzel of Virginia Commonwealth University, a longtime sepsis researcher.

How did such a diverse array of compounds, from so many different companies, fail? Investigators have suggested several reasons. A 10-year study published online in February revealed serious flaws in the animal research on which sepsis drug trials were based. Severe inflammatory responses in mice, it turns out, do not accurately mimic sepsis in people—so a drug that helps mice could make things worse for a person. In addition, patients in sepsis trials may have been too sick to respond well to any drug. Because sepsis patients are seldom diagnosed early, by the time they are enrolled in a trial they are likely to be more challenging to treat. Furthermore, people with sepsis may not all be sick in exactly the same way, so individuals may respond quite differently to the same compound.

"Where we are currently is similar to diagnosing people with 'cancer' without giving them any further information—not that they have leukemia, not what cell type, not what molecular abnormalities are present," O'Brien explains. "'Sepsis' is a bucket that contains different groups of patients. We have not done the groundwork of separating out their underlying pathophysiology."

NEW IDEAS

DESPITE THE MANY DISAPPOINTMENTS, researchers continue to search for treatments that could halt sepsis before it becomes deadly. Spectral Diagnostics in Toronto, for example, pairs a diagnostic blood test with a therapeutic device. The test looks for endotoxin, a molecule that is released from dying bacteria and can trigger the start of sepsis. About 50 percent of sepsis patients, often the most critically ill, have high levels of endotoxin in their blood. Blood is drawn from these patients and pumped over a filter infused with an antibiotic that binds to endotoxin, removing the molecule before the blood is returned to patients. The FDA has approved the test (the filter already existed, and Spectral has licensed it), and the combination of diagnostic and device is currently being tested in 14 U.S. states and in Canada in a large trial.

Spectral acknowledges that its treatment, even if successful, would not help patients who do not have high levels of endotoxin. But "if our trial turns out positive, we could potentially save 50,000 lives per year," says Paul Walker, Spectral's chief executive officer and a critical care specialist.

Richard Hotchkiss, who is a professor of anesthesiology, medicine and surgery at the Washington University School of Medicine in St. Louis, has proposed a very different approach—not just to treatment but to the whole way of thinking about sepsis as well. He sums up his view of the current research landscape as: "Just because you're traveling down a well-worn path doesn't mean you're heading in the right direction."

Although current dogma explains sepsis as a sustained, excessive inflammatory response, Hotchkiss bases his approach on evidence to the contrary. His studies, which include examination of cells extracted from patients soon after death, suggest that the symptoms of sepsis persist because during the course of the illness, the immune system shifts from an overreaction to a kind of collapse—instead of doing too much, it does too little. If that is correct, Hotchkiss says, then immune-stimulating compounds such as interleukin-7, which are already used in cancer treatment, could prevent deaths from sepsis—an idea that traditional sepsis researchers might view as adding fuel to a fire.

With no new drugs on the horizon, some investigators urge a shift in focus from discovering pharmaceutical treatments to the importance of critical care, improved long-term care and increased public awareness. They point out that while the death rate from sepsis remains high, it has decreased over time, not because of new treatments for sepsis but because doctors have in general become better at saving the lives of critically ill patients. Clinicians should pay more attention to the four fifths of sepsis patients who survive, some researchers argue. Many survivors have profound disabilities, such as amputated limbs, blindness and cognitive problems. O'Brien, the Sepsis Alliance adviser, emphasizes that public awareness encourages early recognition, which greatly enhances the chances of recovery. SA

Early Warning Signs

A diagnosis of sepsis requires at least two of these symptoms, as well as a suspected or confirmed infection of bacteria, viruses or fungi. The earliest symptoms of sepsis often mimic a mild infection, but the disease can worsen swiftly, ravaging the body.

- **Quickened breathing** (respiratory rate > 20 breaths/min)
- **Increased heart rate** (> 90 beats/min)
- **Unusually high or low core body temperature** (< 36° Celsius or > 38° C)
- **Unusually high or low numbers of white blood cells**

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David Pogue is the personal-technology columnist for the *New York Times* and an Emmy Award–winning correspondent for *CBS News*.

Disappointment of Dazzling Displays

Your digital screen has more pixels than ever, but all that visual detail comes at a cost

When Apple unveiled its Retina screen on the iPhone 4, the world gasped. "There has never been a more detailed, clear, or viewable screen," read a review on the tech Web site Engadget. "Staring at that screen is addictive," said *Wired* magazine.

What they were reacting to was the superhigh resolution. The iPhone 4 packed in 326 pixels per inch (ppi)—pixels so tiny that you can't discern them at standard viewing distance. Apple went on to incorporate Retina displays into the iPad (264 ppi) and MacBook Pro laptops (227 ppi).

So began the Resolution Wars. Recent phones from Samsung, Nokia and HTC pack in 316, 332 and 440 ppi, respectively. Google's Nexus 10 tablet leapfrogs the iPad with 300 ppi.

And now the television industry has joined in. It is pushing 4K sets—that's four times the resolution of high-definition TV. *Four times.*

Now, up to a point, higher resolution really does look better. Yet there are some footnotes.

Low-resolution graphics look no better on a high-resolution screen. If you've programmed an iPhone app, you know that it doesn't look any sharper until you *reprogram* it for the sharper screen. Until then, the phone just applies pixel doubling (substitutes four pixels for every one on the lower-res screen), which doesn't improve sharpness.

In fact, they look worse. You may remember that when HDTV came out, standard-definition broadcasts actually looked worse than they did on standard TVs. (They still do.) Well, guess what? Same thing happens on other screens.

In theory, standard-res graphics on a high-res screen look exactly as sharp as they always did, thanks to pixel doubling. Yet as many MacBook purchasers discover with dismay, pre-Retina graphics look *worse* on Retina screens. This might be because a standard screen smooths out gaps between pixels, but on a Retina screen the gaps are so tiny, the subtle smoothing goes away.

In any case, the problem is especially severe on the biggest app of all: the Web. Few Web sites have been rewritten to accommodate Retina-type screens, so their graphics usually look awful.

Bigger = slower. Even if Web designers do get around to designing high-res versions of their graphics, those files will be bigger and therefore slower to load. On cellular phones and tablets that dole out Internet service by the megabyte, they are also more expensive. Do we want to wait longer and pay more to have those sharper Web sites? Shouldn't we be able to choose?

Already our Internet providers impose monthly data limits. Do we really want each Web site to eat up, say, four times our monthly data?

Sharp text should be automatic but isn't always. The previous points do not apply to text. Text is not graphics. Whenever a program or Web page displays text, Apple's Retina software automatically delivers extremely sharp characters to your screen.

Unfortunately, that's true only if the software companies use Apple's prescribed text-handling routines, and not all of them do. For example, documents in Adobe's InDesign layout program look horrible.

4K TV broadcasts? Forget it. The Retina-zation of television is particularly absurd. No cable or satellite company will send out 4K broadcasts because, in the bandwidth space of one 4K channel, providers could send out *four* HDTV channels. (Companies already send out low-res versions of HDTV channels to conserve bandwidth.)

The data required for a 4K video is also too great for DVDs, Blu-ray discs or Internet streaming. So what, exactly, will you watch on a 4K set?

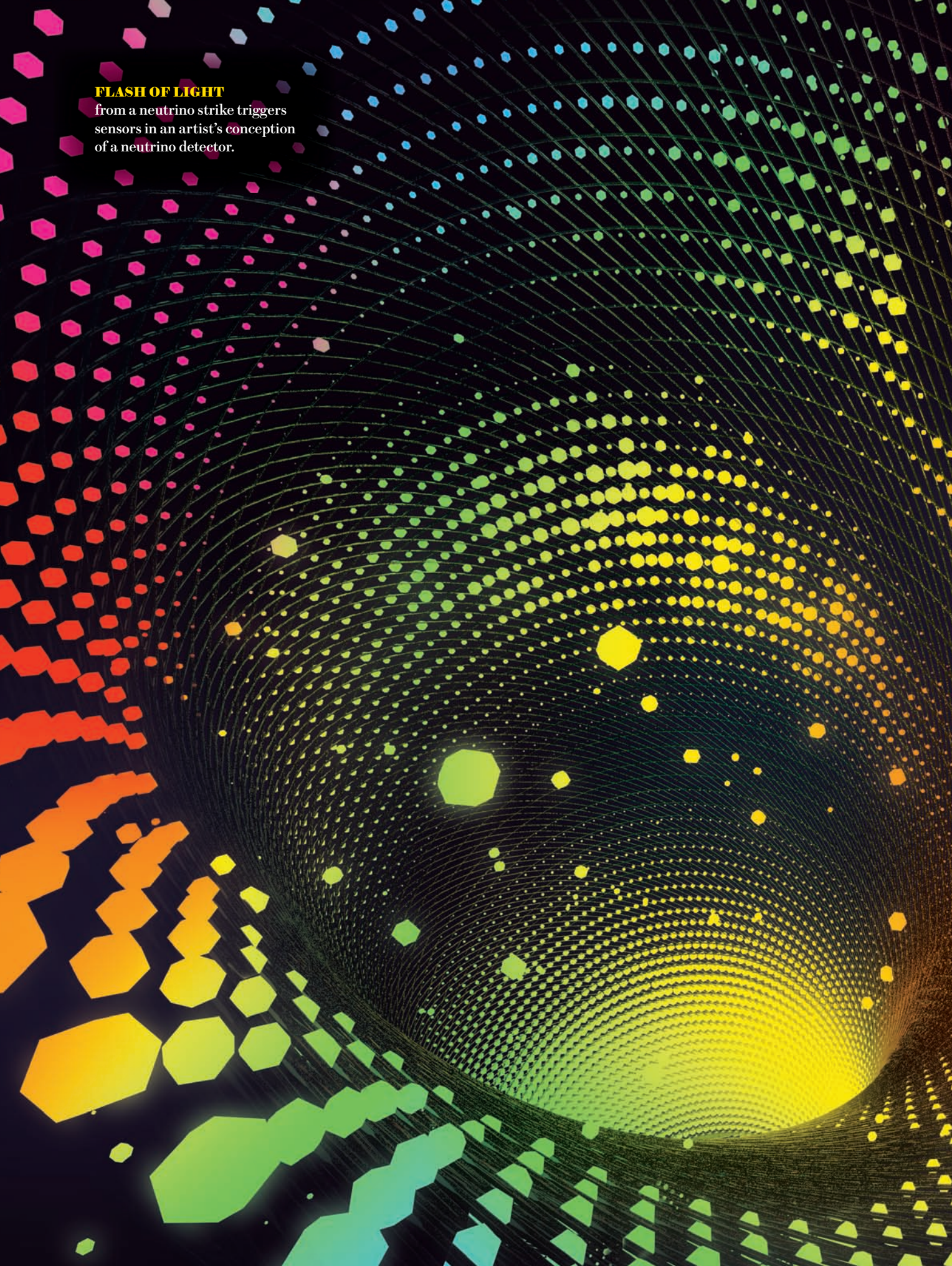
If you buy a Sony 84-inch 4K set ($25,000), the company will loan you a hard drive containing 10 Sony movies in 4K.

That's it? We're going to ship hard drives?

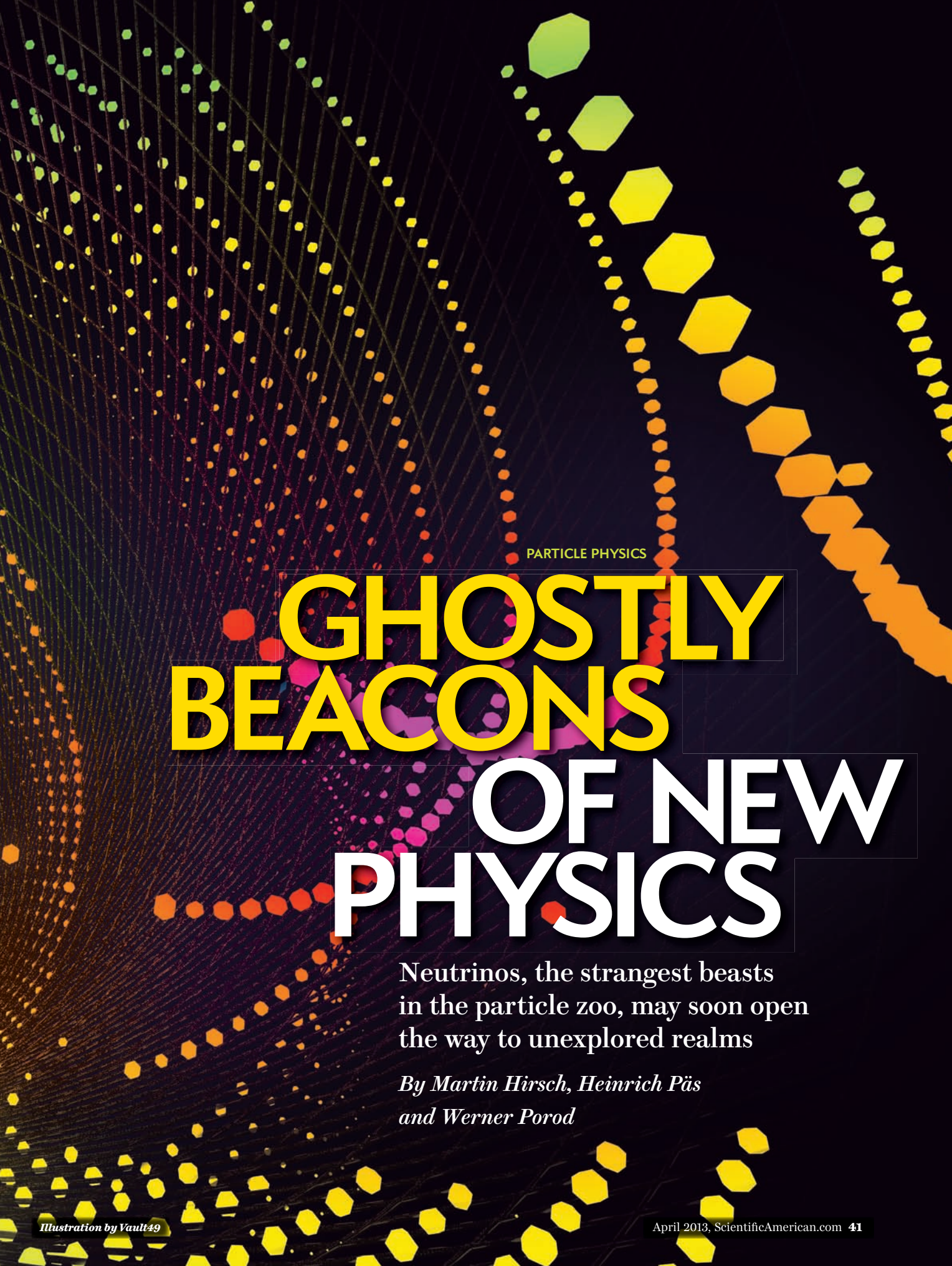
The hardware we need for our superhigh-resolution future is here. Now we need to figure out—on our phones, Web sites and TVs—how we're going to squeeze in all that high-res content.

SCIENTIFIC AMERICAN ONLINE
Test superhigh-res marketing claims with math: ScientificAmerican.com/apr2013/pogue

Illustration by Thomas Fuchs



FLASH OF LIGHT
from a neutrino strike triggers sensors in an artist's conception of a neutrino detector.



PARTICLE PHYSICS

GHOSTLY BEACONS OF NEW PHYSICS

Neutrinos, the strangest beasts in the particle zoo, may soon open the way to unexplored realms

By Martin Hirsch, Heinrich Päs and Werner Porod

Illustration by Vault49

Martin Hirsch is a professor in the Astroparticles and High-Energy Physics Group at IFIC, a joint center for particle physics at the University of Valencia and the Spanish National Research Council.

Heinrich Päs is a professor at the Technical University of Dortmund in Germany. *The Perfect Wave*, his book on neutrinos, is forthcoming from Harvard University Press.

Werner Porod is a professor at the University of Würzburg in Germany.

FEW PHYSICISTS HAVE HAD THE PRIVILEGE OF BRINGING A NEW ELEMENTARY PARTICLE into the world. When Wolfgang Pauli hit on the idea of the neutrino in 1930, however, internal misgivings tempered his response. "I have done a terrible thing," Pauli later told his colleagues. "I have postulated a particle that cannot be detected."

The neutrino is indeed elusive—its ghostly nature allows it to slip through almost all physical barriers, including the materials that physicists use in their particle detectors. In fact, most neutrinos pass cleanly through the earth without so much as brushing against another particle. Yet Pauli's fears turned out to be slightly overblown: the neutrino can be detected—although doing so requires great effort and experimental ingenuity.

Neutrinos are the oddest of the fundamental particles on other grounds as well. They do not make up atoms, nor do they have anything to do with chemistry. They are the only electrically neutral matter particles. They are extremely light—less than a millionth the mass of the next-to-lightest matter constituent, the electron. And neutrinos, more than other particles, metamorphose; they shift among three varieties, or "flavors."

These tiny particles have kept physicists in continuous astonishment for more than 80 years. Even today fundamental questions about the neutrino remain unanswered: Are there only three flavors of neutrino, or do more exist? Why are all neutrinos so lightweight? Are neutrinos their own antimatter counterparts? Why do neutrinos shift character with such amazing verve?

Around the world—at particle colliders, at nuclear reactors, in abandoned mine shafts—new experiments that can address these questions are coming online. The answers they deliver should provide essential clues to the inner workings of nature.

The neutrino's oddities make it a lodestar guiding particle physicists on the daunting voyage toward a so-called grand uni-

IN BRIEF

The neutrino is the oddest breed of fundamental particle. Neutrinos seem to defy all precedents set by better understood varieties of particles, such as electrons and quarks.

Lightweight, shifty and exceedingly difficult to detect, neutrinos have been vexing experimentalists for decades.

Even today fundamental properties of neutrinos remain up for debate. Some of the key questions pertain to the origin of their meager masses, the nature of neutrino antimatter and the number of neutrino species in existence, not to mention their penchant for switching identities on the fly.

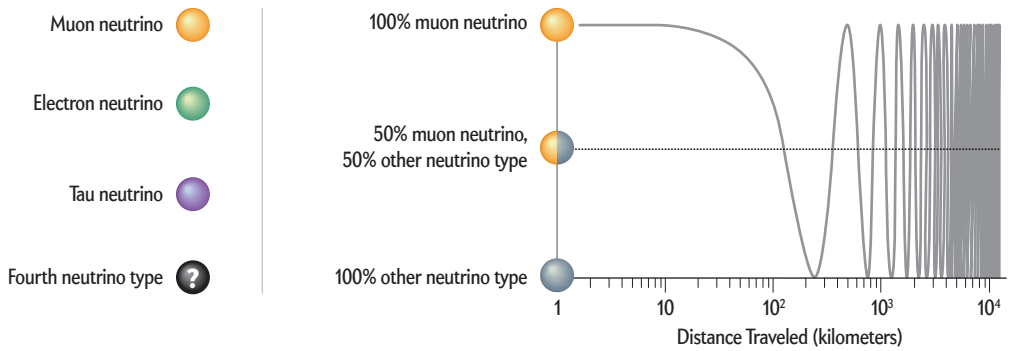
Uncovering the true nature of the neutrino may pave the way to a more unified theory of physics.

Changing Identities on the Fly

As neutrinos propagate, at nearly the speed of light, through space, the earth or your body, they change identities often, oscillating between three known neutrino types. Their behavior is odd but not entirely random—the properties of neutrinos allow physicists to predict the probability of their oscillation over various distances.

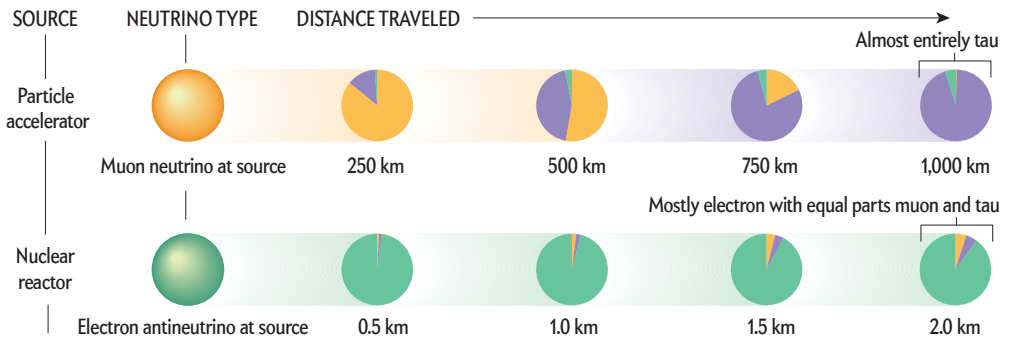
Flavor Palette

Neutrinos come in at least three flavors: the electron, the muon and the tau. (Some physicists suspect the existence of a fourth neutrino as well.) The graph below illustrates the probability that a muon neutrino, having traversed a given distance, will switch flavors. In practice, oscillation distances depend on the neutrino's energy.



Classic Morphs

Neutrino oscillation experiments measure the flavor divergence between the particles emitted by a neutrino source and those captured at a distant detector. The illustration below shows idealized source-to-detector oscillation patterns for experiments at particle accelerators and nuclear reactors.



fied theory describing all particles and forces, except gravity, in a consistent mathematical framework. The Standard Model of particle physics, the best theory of particles and forces to date, cannot accommodate all the complexities of the neutrino. It must be extended.

LIGHTWEIGHT BUT PRESSING

THE MOST POPULAR WAY to build on the neutrino segment of the Standard Model is to introduce new entities called right-handed neutrinos. Handedness is a variant of electrical charge that determines whether a particle feels the weak interaction, the force responsible for radioactive decay; a particle must be left-handed to feel the weak force. These hypothetical right-handed particles would thus be even slipperier than their left-handed fellows, the experimentally proved neutrinos of the Standard Model. All neutrinos are classified as leptons—the extended family of particles that also includes the electrons—meaning that they do not feel the strong force holding together the protons and neutrons in the atomic nucleus. Lacking electrical charge, neutrinos do not directly feel electromagnetic forces, either. That leaves only the force of gravity and the weak interaction for the three known neutrino flavors, but a right-handed neutrino would be impervious even to the weak force.

If a right-handed neutrino exists, it would provide a very reasonable explanation for another neutrino puzzle: the reason the three left-handed varieties—the electron, muon and tau neutrinos—all have such tiny masses.

Most elementary particles gain their mass by interacting with the ubiquitous Higgs field. (Higgs became a household name last year when physicists at the Large Hadron Collider, or LHC, at CERN near Geneva announced they had identified a new particle matching the description of the long-sought Higgs boson. That boson is the particle counterpart to the Higgs field, just as the photon is the counterpart to the electromagnetic

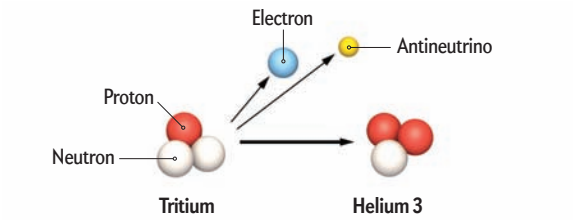
Graphic by Jen Christiansen

The Heart of the Antimatter

A number of experiments around the globe have been built to observe a rare nuclear physics phenomenon called double beta decay. These experiments aim to test the hypothesis that, within the realm of neutrinos, matter and antimatter are one and the same. If neutrinos are indeed their own antiparticles, they could alter the balance of matter and antimatter, potentially explaining how matter came to dominate the universe.

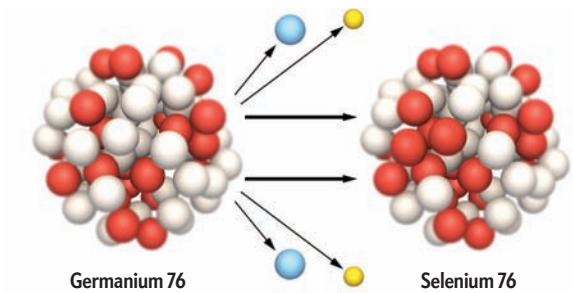
Single Beta Decay

Radioactive nuclei can settle into more stable configurations via beta decay. Here tritium (an isotope of hydrogen) decays to helium 3 by transmuting a neutron into a proton, shedding an electron and an antineutrino in the process.



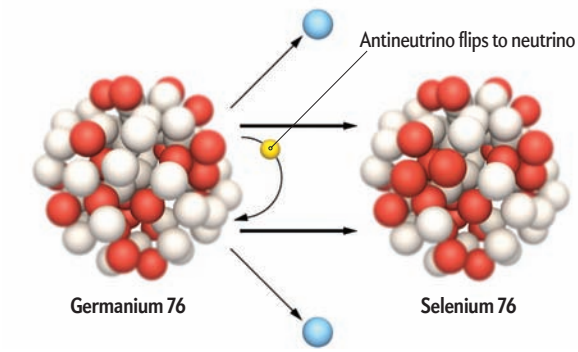
Double Beta Decay

A handful of nuclear isotopes can undergo two beta decays at once—switching two neutrons into protons, which emits two electrons and two antineutrinos.



Neutrinoless Double Beta Decay

If neutrinos are their own antiparticles, the neutrino part of the decays could cancel out—in one decay a neutrino would be absorbed instead of an antineutrino being emitted. Such neutrinoless decay has not yet been convincingly observed.



field.) In the process, the Higgs carries away the particles' weak force version of electrical charge. Because right-handed neutrinos lack this charge, their mass does not rely on the Higgs field. Instead it may emerge from a different mechanism altogether at the extremely high energies of grand unification, which would make the right-handed neutrino enormously heavy.

Quantum effects could link right-handed neutrinos to their left-handed siblings in a way that would cause the enormous mass of one to "infect" the other. The contagiousness would be very weak, though—if the right-handed neutrino came down with pneumonia, the left-handed one would catch only a minor cough—which means the left-handed mass would be very tiny. This relation is known as the seesaw mechanism because a large mass raises, or lifts up, a smaller mass.

An alternative explanation for neutrino masses arises from supersymmetry, a leading candidate for new physics beyond the Standard Model. In the supersymmetry hypothesis, every particle within the Standard Model has an as yet undiscovered partner. The so-called superpartner particles, which must be exceedingly massive to have thus far escaped detection, would instantly at least double the number of elementary particles. If supersymmetric particles exist, the LHC may be able to produce them and measure their properties.

One of the most appealing traits of supersymmetry is that a superparticle known as the neutralino makes a fine candidate for dark matter—the mass in galaxies and galaxy clusters that exerts a gravitational pull but does not emit light nor reveal itself in other obvious ways. The neutralino would fit the bill for dark matter only if it were stable over long periods, rather than decaying away rapidly to some other particle.

A short-lived neutralino would thus send dark matter researchers back to the drawing board but could prove a boon to neutrino physicists. The neutralino's stability depends on a hypothetical property called R-parity, which prevents the superpartners from decaying into any of the ordinary Standard Model particles. If R-parity does not hold, however, the neutralino becomes unstable—and its decay depends in part on the mass of the neutrino.

Two of us (Hirsch and Porod), in collaboration with José Valle of the University of Valencia in Spain and Jorge C. Romão of the Technical University of Lisbon in Portugal, have shown that the link between neutrinos and the neutralino could be testable at the LHC. If the stability of the neutralino indeed depends on neutrinos, the neutralino's lifetime would be predictable from known neutrino properties. And it just so happens that the superparticle should exist long enough for physicists to track its entire lifetime—from production to decay—inside the detectors of the LHC.

WHAT'S THE ANTIMATTER?

ALL PLAUSIBLE EXPLANATIONS for the neutrino's meager masses point to unexplored realms of physics. Yet one of those explanations, the seesaw mechanism, may also bear on the mystery of how matter came to reign over antimatter—a triumph that enabled the formation of cosmic structure and, ultimately, the development of life.

Every particle in the Standard Model has an antimatter counterpart, a sort of Bizarro world version with an opposing charge. The electron, for instance, has an electrical charge of –1,

Illustration by George Retseck

and the antielectron, or positron, has a charge of +1. When an electron and positron collide, their charges cancel out, and the particles annihilate in a burst of radiation. The complete chargelessness of the right-handed neutrino may have an important consequence: it could mean that, for neutrinos, matter and antimatter are one and the same. In the terminology of physics, the electron and positron are known as Dirac particles. A particle that is its own antimatter counterpart, on the other hand, is a Majorana particle.

If the seesaw theory accurately reflects the workings of the particle world, then the left-handed neutrinos are infected not just with mass but also with the Majorana-ness of the right-handed neutrinos. In other words, if some neutrinos are their own antiparticles, then all neutrinos are.

Neutrinos and their antiparticles being one and the same would have a variety of fascinating implications. For instance, neutrinos could trigger transitions among particles and antiparticles. In most particle reactions, the so-called lepton number, or the number of leptons minus the number of antileptons, is conserved—it does not change. Neutrinos, however, might violate this rule, creating an imbalance of matter and antimatter. For us humans, the imbalance is a very good thing because if matter and antimatter were equally paired in the aftermath of the big bang, they would have completely annihilated each other and left nothing behind to build galaxies, planets and life-forms. The explanation for matter's dominance over antimatter has long eluded physicists and cosmologists.

At particle colliders, at nuclear reactors and in abandoned mine shafts, next-generation neutrino experiments are now coming online. They should provide essential clues to the inner workings of nature.

DISAPPEARING ACT

THE CONNECTION between neutrinos and their antiparticles does not have to languish in the realm of tantalizing but ultimately unsettled theory. Many experiments, past and present, have sought to answer definitively whether neutrinos are in fact their own antiparticles by searching for a type of radioactive event known as nuclear double beta decay.

Neutrinos and antineutrinos were first observed in nuclear beta decay, by which an atom emits an electron, along with an antineutrino. In several nuclear isotopes, two beta decays can occur simultaneously, which, under normal circumstances, emits two electrons and two antineutrinos. Yet if the neutrino is a Majorana particle, then the same antineutrino emitted in the first decay can be absorbed in the second. The result is a double beta decay that does not emit any neutrinos or antineutrinos [*see box on opposite page*]. In an instant, where there had previously been no leptons, two leptons (the electrons) emerge without their usual, counterbalancing antileptons (the antineutrinos). In other words, this so-called neutrinoless double beta decay violates the conservation of the lepton number.

At present, the search for neutrinoless double beta decay is the best test we have for Majorana neutrinos in particular and for lepton number violation in general. In principle, a neutrinoless double beta decay experiment is simple: collect a nuclear isotope such as germanium 76, in which simultaneous beta decays can occur, and wait for the emergence of two electrons unaccompanied by neutrinos. In practice, however, the experiments are very difficult. Double beta decay of any kind is exceedingly rare, so experimenters must gather large quantities of germanium, or other source materials, to have a hope of documenting the neutrinoless variety. To make matters worse, the constant stream of subatomic particles raining down on the earth from cosmic rays tends to drown out the minuscule signal from double beta decays. So experimentalists must bury their detectors deep underground or in former mines or other subterranean labs, where the overlying rock screens out nearly all cosmic rays.

Unfortunately, the only report to date of neutrinoless double beta decay, from the Heidelberg-Moscow Double Beta Decay Experiment in Italy, has been vigorously contested by other physicists. Next-generation detectors just starting to take data or currently under construction will conduct a more thorough search. An experiment in New Mexico called EXO-200 and another one in Japan called KamLAND-Zen recently published the first data from their searches for neutrinoless double beta decay, which caused friction with the earlier claim but did not unambiguously rule it out.

The GERDA experiment in Italy, which came online in 2011, uses the same isotope as the Heidelberg-Moscow setup in an improved design that aims to directly confront its predecessor's controversial finding. Both the EXO-200 and KamLAND-Zen experiments are continuing their operations, and an apparatus known as CUORE is scheduled to start taking data in Italy in 2014. The number of advanced experiments now under way provides a very reasonable hope that neutrinoless double beta decay may be confirmed before the end of this decade.

LIGHT SWITCHERS

FINDING AN AS YET UNDISCOVERED neutrino or proving that neutrinos and antineutrinos are one and the same would add an entirely new layer of intrigue to these already puzzling particles. But even as we physicists hunt for new facets of these particles, we continue to wrestle with the mechanism underlying a well-documented but poorly understood attribute of neutrinos—their strong propensity to metamorphose. In the literature, we say that the amount of lepton flavor violation, or neutrino mixing, is large in comparison with the mixing among flavors of quarks, the elementary particles that make up protons and neutrons.

Many research groups worldwide are investigating how newly conceived symmetries of nature—key commonalities between apparently distinct forces and particles—could explain such behavior. One example would be the symmetries inherent in the ways that the known particles transform from one to another. Gautam Bhattacharyya of the Saha Institute of Nuclear Physics in Calcutta, Philipp Leser of the Technical University of Dortmund in Germany and one of us (Päs) recently discov-

The Neutrino's Secrets, Written on the Sky

By Sudeep Das and Tristan L. Smith

Measuring the minuscule mass of neutrinos has so far proved impossible—and not for lack of trying. Numerous laboratory experiments over the past few decades have succeeded only in placing loose limits on the three neutrino masses.

We have very compelling reasons to expect that the best way to measure the mass of these tiny particles is, surprisingly, to look for their influence at the largest scales of the universe. For although neutrinos are virtually massless and nearly invisible, their sheer numbers—some 10^{89} in the universe—make them very consequential players in the cosmos.

Our logic goes like this: Early in the history of the universe, when everything was very hot and dense, nuclear reactions forged helium from hydrogen, releasing huge numbers of neutrinos as a by-product. As the universe evolved, expanded and cooled, small fluctuations in the density of this primordial particle soup were amplified; in regions of above-average density, gravity tried to pull more material in.

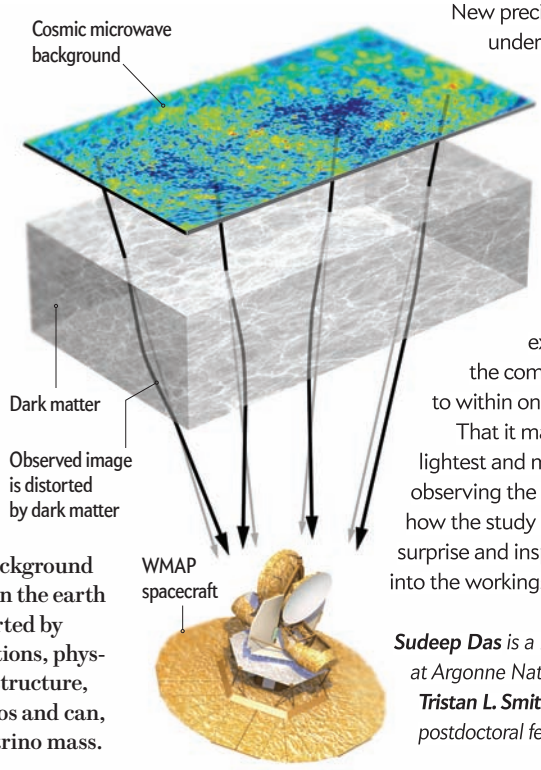
Dark matter, the essentially invisible stuff that accounts for a goodly portion of the universe's mass, collapsed into clumps first because it only interacts through gravity. These initial clumps of dark matter formed the seeds of the galaxies and the clusters of galaxies that we see today. Neutrinos, being extremely light, began to clump somewhat later on in the universe's development. In fact, by zipping so freely through the cosmos, neutrinos have actually slowed the clumping of dark matter—an effect that should be detectable today.

The more massive the neutrinos, the more they will have hindered the clumping of matter—in effect, blurring the edges in the large-scale structure of the universe. By measuring how matter is distributed in the universe, then, we can infer how massive neutrinos are.

Mapping the distribution of matter—most of which is dark matter—is hardly straightforward. Yet researchers have seen that the leftover radiation from the big bang, known as the cosmic microwave background (CMB), is slightly distorted because of the light-bending gravitational effects of dark matter clumps that fill the space between the CMB and us. Examining this "gravitational lensing" of the CMB is a very promising way of measuring the distribution of dark matter in the universe.

New precision measurements of the CMB now under way will enable us to measure the lensing distortions to very high accuracy, effectively mapping out the otherwise invisible dark matter. If the distribution of dark matter is confined to sharp-edged structures separated by voids, we can infer that the neutrino masses are small; if instead the edges are blurred, we will know that the neutrino masses are larger. The new generation of CMB experiments should allow us to pin down the combined masses of the three neutrino types to within one five-millionth of the mass of the electron.

That it may be possible to measure the mass of the lightest and most elusive of subatomic particles by observing the entire universe is just another example of how the study of physics, across all scales, continues to surprise and inspire astrophysicists to delve ever deeper into the workings of the natural world.



WARPED: Cosmic microwave background radiation collected by telescopes on the earth and in space has been subtly distorted by dark matter. By tracing the distortions, physicists can chart the dark matter's structure, which has been shaped by neutrinos and can, in turn, place strict limits on neutrino mass.

Sudeep Das *is a David Schramm postdoctoral fellow at Argonne National Laboratory.*

Tristan L. Smith *is a Berkeley Center for Cosmological Physics postdoctoral fellow at the University of California, Berkeley.*

ered that such symmetries would conspicuously affect the Higgs field. The interaction of flavor-swapping quarks and neutrinos with the Higgs field would manifest itself in exotic decay products of Higgs bosons that ought to be observable at the LHC. Such a signal could point to the underlying mechanism for neutrinos' hyperactive transmutations, which would certainly be one of the most spectacular discoveries at the LHC.

In the meantime, a different family of experiments is nailing down just how often the particles switch identities. Long-baseline experiments such as T2K in Japan, MINOS in Minnesota and OPERA in Italy detect beams of neutrinos that originate at particle accelerators hundreds of kilometers away, to measure changes in flavor as neutrinos traverse long distances through the earth [*see box on page 43*]. The scales of these experiments are so large that the neutrinos may cross state lines or even international borders on their journeys. (In 2011 OPERA made news when physicists from the collaboration announced that neutrinos in their experiment appeared to travel from CERN to

Illustration by George Retseck

an underground Italian lab faster than the speed of light—a measurement that soon proved to be flawed.) In complement to these long-distance neutrino experiments, the Double Chooz project in France, the Daya Bay Reactor Neutrino Experiment in China and RENO in South Korea all measure the short-range oscillation of neutrinos coming from nuclear reactors.

Only in 2012 did these experiments finally determine the last and smallest of the so-called mixing angles—the parameters governing the transitions among neutrino flavors. The final mixing angle to be pinned down, known as the reactor angle, describes the probability of an electron neutrino or antineutrino's conversion over a short baseline. The measurements of the reactor angle opened the possibility that future neutrino experiments might be able to compare the properties of neutrinos and antineutrinos. An asymmetry between particles and their antimatter counterparts would be known as CP violation and, along with studies of neutrinoless double beta decay, could bear on the mystery of why there is more matter than antimatter in our universe.

Of the ongoing searches, T2K probably has the first decent chance to see hints of CP violation. But the race is on among this new generation of experiments to answer key neutrino questions—and it promises to be exciting. The long-baseline NOvA experiment, now under construction in the U.S., also has the potential to uncover CP violation in neutrinos. NOvA will fire a neutrino beam through the earth from Fermi National Accelerator Laboratory in Batavia, Ill., clear across the state of Wisconsin and the tip of Lake Superior, to a detector in Ash River, Minn., 810 kilometers away. The neutrinos will make the trip in less than three milliseconds.

Among its research goals, NOvA also aims to clarify the neutrino mass hierarchy—determining which of the neutrinos is the lightest and which is the heaviest. At present, physicists know only that at least two neutrino species have nonzero masses, but, as with so many aspects of these ghostly particles, the details elude us.

Any asymmetry between neutrinos and their antimatter counterparts could bear on a mystery that has long vexed physicists and cosmologists: why there is more matter than antimatter in our universe.

LINGERING MYSTERIES

WITH SO MANY NEUTRINO EXPERIMENTS under way—featuring different aims, different designs and different particle sources—the varied data emerging from around the globe have sometimes yielded conflicting interpretations. One of the most tantalizing—and controversial—experimental hints suggests the existence of a new particle called the sterile neutrino.

Echoing Pauli's fears in 1930, the sterile neutrino would be only indirectly detectable, just like the much heavier right-handed neutrino of the seesaw mechanism. (From a theoretical point of view, however, the two proposed particles are nearly mutually exclusive.) Nevertheless, two experiments may have caught a whiff of the sterile neutrino. LSND, which ran at Los Alamos National Laboratory in the 1990s, found early but controversial evidence for an elusive type of neutrino flavor conversion—muon antineutrinos morphing into electron antineutrinos. Fermilab's MiniBooNE, which began producing scientific results in 2007, also hinted at such conversions. Yet the LSND and MiniBooNE oscillations did not fit neatly into the standard three-neutrino picture.

Quantum mechanics permits neutrinos to oscillate between flavors only if they have mass—and only if each flavor has a different mass. The various neutrino masses could trigger neutrino conversion to explain the LSND and MiniBooNE anomalies but only if another mass difference exists in addition to the ones already known—in other words, only if four neutrino types exist instead of three. An additional neutrino coupling to the weak force would make the Z boson—a carrier of the weak force—decay too fast, so this particle would not interact with the weak force at all. Hence the "sterile" designation: this hypothetical neutrino would be almost entirely decoupled from the rest of the particle zoo.

Detectors of a different kind altogether, which capture neutrinos from nearby nuclear reactors, have also registered surprising results that could point to a sterile neutrino. The data from several reactor experiments indicate an anomalous disappearance of electron antineutrinos over very short distances, which, if interpreted in terms of neutrino oscillations, would imply the existence of sterile neutrinos. The anomaly has been around for some time, but recent recalculations of the neutrino output from the various reactors have strengthened the case for a new particle.

The evidence for sterile neutrinos, such as it is, remains sketchy, indirect and conflicted—all of which is to be expected in pursuit of a notoriously elusive, and possibly nonexistent, particle. Yet MiniBooNE and a companion experiment called MicroBooNE, which is now under construction at Fermilab, may soon have something firmer to say on the matter. And a new crop of proposed experiments, which would study the reactor anomaly, is also under discussion.

It is remarkable that the mighty LHC and the comparatively low-energy experiments on the humble neutrino provide such complementary routes to explore the inner workings of nature. More than 80 years after Wolfgang Pauli conceived of his "particle that cannot be detected," neutrinos continue to guard their secrets closely. Still, the potential payoff in unraveling those secrets justifies the decades-long effort to pry ever further into the neutrino's private life. SA

MORE TO EXPLORE

Testing Neutrino Mixing at Future Collider Experiments. W. Porod, M. Hirsch, J. Romão and J.W.F. Valle in *Physical Review D,* Vol. 63, No. 11, Article No. 115004; April 30, 2001.

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SCIENTIFIC AMERICAN ONLINE

View a slide show of neutrino experiments (and their exotic settings) around the world at ScientificAmerican.com/apr2013/neutrino

SPECIAL REPORT

THE FUTU MEDI

BOOSTING THE BODY'S HEALING POWERS

IN BRIEF

The emerging field of regenerative medicine may one day revolutionize the treatment of heart disease and neurodegenerative disorders, solve the organ donor shortage problem, and completely restore damaged muscles, tendons and other tissues.

The key, researchers are learning, is to give the body a kind of starter kit—made of various proteins, fibers or cells—or to clone extra copies of the semispecialized stem cells that are already found in adult patients and to allow the body to take over from there.

The extra help allows the body to regrow tissues of the type or in the amount that it normally could not do by itself. Already such self-healing treatments have somewhat rejuvenated a few patients' ailing hearts and helped surgeons repair injured muscles.

RE OF CINE

Unique among the human body's larger organs, the liver has a remarkable ability to recover from injury. An individual can lose a big chunk of it in an accident or during surgery, but as long as at least a quarter of the organ remains intact and generally free of scars, it can grow back to its full size and function. Alas, this capacity for self-regeneration does not hold for other body parts. A salamander can regrow its tail, but a person cannot regain an amputated leg or renew sections of the brain lost to Alzheimer's disease. For this feat, humans need help—and that is the promise of an emerging field of research called regenerative medicine.

Stem cells—progenitor cells that can give rise to a variety of tissues—play an important role in this endeavor. Scientists are learning how to mix a hodgepodge of sugar molecules, proteins and fibers to create an environment in which the stem cells can develop into replacement tissue. As the following stories show, investigators have made strides in replacing damaged heart tissue and rebuilding muscle. They are also in the early stages of developing new nerve cells. Some of these advances could emerge from the lab as treatments in a few years, or they may take decades, or they may ultimately fail. Here are a few of the most promising ones. *—The Editors*

A Change of Heart

Stem cells may transform the way doctors treat heart failure

By Ferris Jabr

HEART REPAIR
Harvesting semispecialized stem cells from an ailing heart, helping them to make millions of copies of themselves and injecting those cells into the heart enable the organ to break down scar tissue and grow new muscle.

IN EARLY 2009 Mike Jones bought a newspaper at a convenience store in Louisville, Ky., and read about a local doctor who wanted to try something unprecedented: healing an ailing heart by harvesting and multiplying its native stem cells—immature cells with regenerative powers. Jones, then 65, had congestive heart failure: his heart was no longer pumping blood efficiently. He contacted the doctor, Roberto Bolli of the University of Louisville, and in July of that year Jones became the first person in the world to receive an infusion of his own cardiac stem cells.

Before treatment, Jones could barely climb stairs. Today he feels well enough to chop his own firewood and clear fallen tree limbs from his nine-acre property. His "ejection fraction," a measure of how much blood the heart pumps from one chamber to another, increased from 20 to 40 percent in the two years following the experimental treatment—lower than a typical level (in the 55 to 70 percent range) but still a dramatic improvement.

Since then, hundreds of other patients with heart damage have similarly improved after doctors injected them with stem cells extracted from their own heart or bone marrow, as well as stem cells from unrelated donors. Researchers think the stem cells turn into new tissue and stimulate other cells to divide. Many important questions remain unanswered, however. Scientists still do not know which of the different kinds of stem cells work best and how exactly to prepare the cells before treatment—but they are quickly gaining insights. "I think we are at the dawn of one of the biggest revolutions in medicine in our lifetime," Bolli says. "We still need to learn how to use these cells properly—but this is real. In the future, we will collect our own stem cells, grow them and keep them in freezers until we need them."

PRIMING THE PUMP

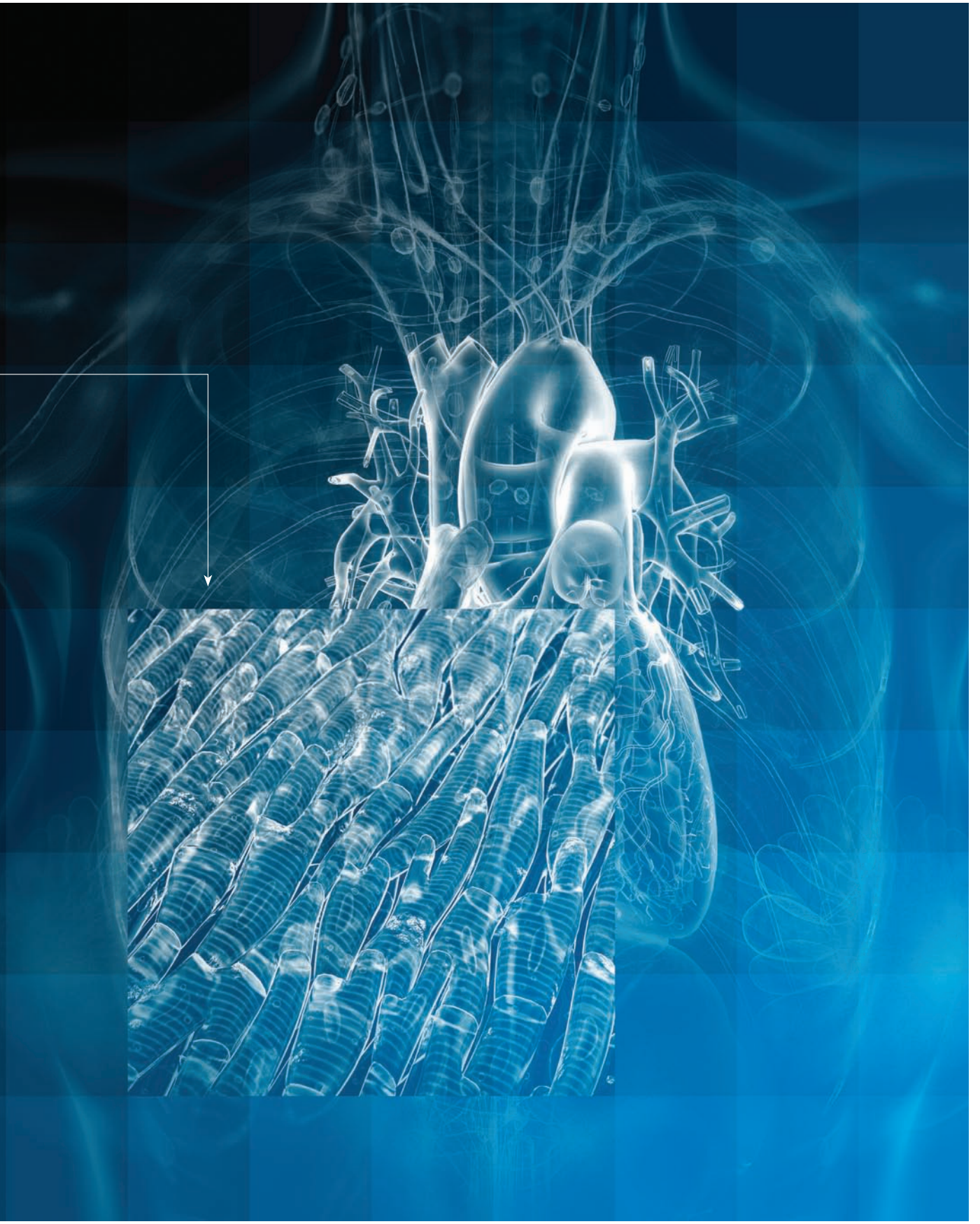
FOR THE PAST FOUR DECADES scientists thought of the human heart as a powerful but vulnerable living pump. Because the adult heart appeared incapable of regenerating its cells, any cell death would irrevocably weaken the organ, researchers reasoned. Now and then, however, a scientist glimpsed adult heart cells dividing under the microscope. Carbon dating of preserved heart tissue has since confirmed that the adult heart replaces its cells throughout life, although this turnover is modest compared with that in the gut and skin. Biologists now estimate that the heart replaces 1 percent or more of its four to five billion muscle cells each year. Researchers have also learned that the new cells arise from duplication of mature heart cells as well as from stem cells embedded in the heart.

These native stem cells allow the heart to repair itself in small ways. After a heart attack, for example, resident stem cells mature into new heart cells and encourage existing cells to divide. This self-repair lasts only a week or two, however, which is not nearly enough time to replace the more than one billion cells lost in a typical heart attack. The result is a large area of inflexible scar tissue. Just as a car tire bulges where it has been damaged, the human heart swells where it has been scarred; the once efficient football-shaped organ becomes a flabby, ineffectual pump.

Stem cell therapy works by giving the heart a mega dose of its own repair cells. Animal studies indicate that some injected stem cells mature into adult cells, but most die within a few days. Before the cells expire, however, they secrete a cocktail of proteins that encourage healthy heart cells to proliferate, as well as enzymes that break down the collagen fibers in scar tissue, making way for new heart muscle.

So far researchers have completed only a few small trials with patients. Bolli and his colleagues harvested a small piece of heart tissue from each of 23 patients with heart damage or failure, including Jones. The researchers nurtured tiny gardens of the heart cells in petri dishes, filtering out stem cells by searching for a stem cell–specific protein marker known as c-kit. They then allowed the stem cells to make millions of copies of themselves.

Sixteen patients received one million cardiac stem cells each via a catheter fed into the coronary artery, and seven patients received standard care (which consisted mainly of beta blockers and diuretics). Four months later the ejection fraction had increased from a starting average of 30.3 percent to an average of 38.5 percent in patients who received stem cells, but it had barely budged in standard care



Illustrations by Bryan Christie

patients (inching from 30.1 to 30.2 percent). One year after treatment the average weight of scar tissue in stem cell patients had decreased by 30 percent.

In a similar trial, Eduardo Marbán of the Cedars-Sinai Heart Institute in Los Angeles and his colleagues treated 17 patients with their own stem cells and another eight patients with standard care. Marbán and his team used remotely controlled forceps to pinch off peppercorn-size specks of heart tissue to grow in the lab. Whereas Bolli had extracted mainly "true" stem cells displaying c-kit from his lab cultures, Marbán extracted a more diverse mixture of cells—some of which may have a more limited repertoire. Patients who received standard care showed no statistically significant change in scar mass or healthy heart tissue. Stem cell patients showed a 42 percent decrease in scar mass and a 13-gram increase in healthy tissue over one year, although their ejection fraction hardly improved.

Other researchers have attempted to treat heart failure with so-called mesenchymal stem cells derived from bone marrow, which are appealing because they are less likely to become cancerous compared with other stem cells. Mesenchymal stem cells secrete growth factors that prompt nearby cells to multiply and can turn into heart muscle in the right environment. Trial results have been inconsistent so far—some patients clearly improve, whereas others show few or no positive changes.

Joshua Hare of the University of Miami wondered if heart patients would tolerate bone marrow stem cells donated by a stranger or reject them as foreign. Hare gave 15 patients injections of their own bone marrow stem cells, and another 15 people donated cells. Thirteen months later none of the patients in either group had rejected the stem cells, and scar tissue had diminished by more than one third in both groups. Elderly patients may benefit more from the stem cells of young donors than from their own because younger cells have not endured as much wear and tear.

"Up until now, we had no way to remove the scar that follows a heart attack," Hare says. "Showing you can reduce scarring and replace it with new tissue is the home run we have been looking for. I think we will transform the treatment of heart failure."

The Super Glue Cure

Regrowing muscles, tendons and even organs may be possible using nature's own adhesive

By Christine Gorman

FOR YEARS BIOLOGISTS were so focused on the internal workings of cells that they pretty much ignored the "glue" that holds those cells together in a body, human or otherwise. And yet once researchers started looking deeper into the stuff between cells, known as the extracellular matrix, they began to realize just how dynamic the whole arrangement is. Not only does the overlooked matrix provide the biological scaffolding necessary to keep animal tissues and organs from dissolving into a gooey mess, but it also releases molecular signals that, among other things, help the body heal itself.

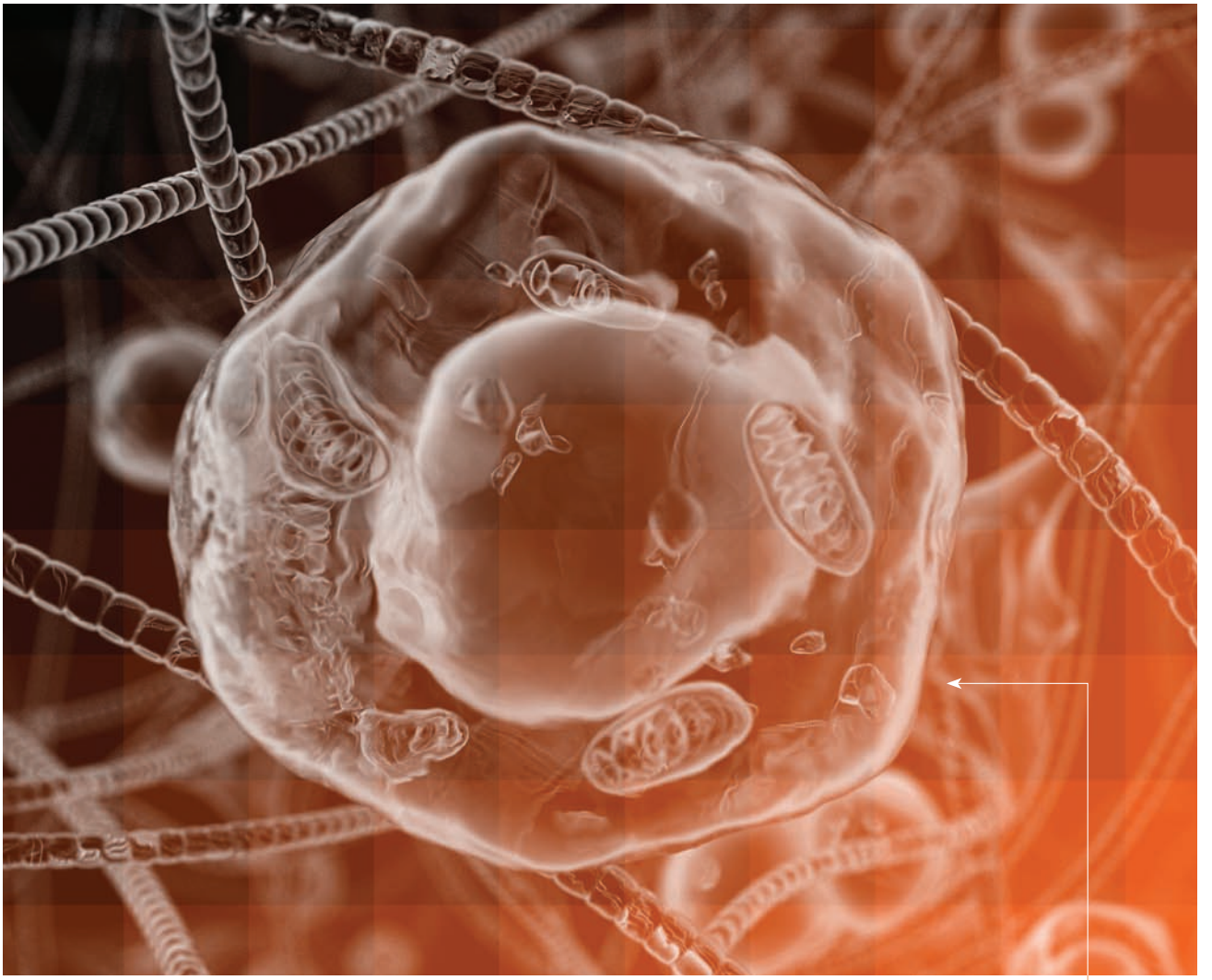
Building on this insight, investigators are now developing a new approach to tissue engineering—one in which the regenerative power of nature's own scaffolding plays a starring role. The idea is to harvest extracellular matrix from, for example, pigs and implant it in patients suffering from a large internal injury (after first stripping away the components that would have triggered a destructive attack by the recipient's immune system). The newly placed scaffold would then release molecules that attract semispecialized stem cells from the rest of the body to fill the various niches and to differentiate into exactly the type of tissue that should be there. Eventually even the implanted latticework would be replaced with human proteins and fibers, entirely erasing all trace of its barnyard origins.

The body easily heals small injuries but must protect itself from large wounds by covering them with scar tissue.

Researchers are turning this vision into reality at an incredibly fast pace. Less than a decade ago surgeons started using extracellular matrix to repair abdominal hernias, basically weak spots in the muscles and supportive tissue that surround the intestines. Currently they are trying to grow new tendons inside the body, and in the not too distant future they hope to regenerate major muscle groups and even organs on a regular basis. Not surprisingly, the U.S. Department of Defense, which has developed a grim expertise in caring for soldiers who have had holes torn into their chest, arms and legs by explosive devices in Iraq and Afghanistan, funded many of these investigations with tens of millions of dollars.

SCARRING VS. REGROWTH

FEW RESEARCHERS are as well poised as Stephen Badylak, deputy director of the McGowan Institute for Regenerative Medicine at the University of Pittsburgh, to help propel the field forward. Badylak began his career as a veterinarian, then received a Ph.D. in pathology, followed by a medical degree. "It's not a very practical



BIOLOGICAL SCAFFOLDING
A cell (*center*) is embedded in a framework of tissue fibers. By removing the cells and implanting the remaining structure, surgeons may coax the body to grow its own replacement organs.

way to train," he notes, "unless you're prepared for a huge amount of educational debt."

Badylak believes extracellular matrix may one day prove particularly beneficial to the survivors of explosions. The mammalian body, he notes, has limited ways in which it can respond to injury. Small wounds, such as paper cuts, disappear after inflammatory cells flood the area, fighting infection and removing damaged tissue. Complete replacement of normal skin (without a scar) soon follows. Soldiers who survive a roadside bombing, on the other hand, may lose 20 to 80 percent of the mass in a particular muscle group. In such severe cases, the researcher says, the injury exceeds the body's ability to regenerate tissue and the gap gets filled with dense scar tissue, thereby connecting the remaining tissue parts but also leading to loss of function. In these cases, the best option may be to amputate the limb and fit the wounded warrior with a prosthetic that provides a broader range of motion.

Badylak and his colleagues are now using extracellular matrix to treat 80 such patients with grave muscle injuries incurred at least six months previously. After an intensive regimen of physical therapy, designed to make sure the body has replaced as much muscle as it possibly can on its own, surgeons reopen the old wounds, remove any scar tissue that has formed, put in the biological scaffold and attach it to nearby healthy tissue.

Early results are promising, the veterinarian-physician-tissue-engineer says. Biopsies of treated muscle have shown the same biochemical changes that investigators saw when developing the technique in animals. If all continues to go well, Badylak hopes to publish findings from the first five patients later this spring or summer.

INNER ANATOMY
An ingenious use of sugar molds coated with cells may allow investigators to replicate the sturdy internal vessels that are needed to carry oxygen deep within larger organs, such as the kidneys (*shown here*), and to remove wastes.

A Sweet Solution for Replacing Organs

To build large organs that work properly, researchers need to find a way to lace them with blood vessels

By Katherine Harmon

THE AUDIENCES at TED talks are used to being wowed as they learn about advances in technology. Even by TED standards, however, the 2011 presentation by Anthony Atala of the Wake Forest Institute for Regenerative Medicine was amazing. Unseen by the audience at first, various vials and nozzles hummed with mysterious activity behind Atala while he was on the stage. About two thirds of the way through the talk, a camera zoomed in on the device's internal armature and showed it weaving back and forth, depositing living cells grown in a laboratory culture layer by layer on a central platform, basing its activity on highly accurate three-dimensional digital renderings. The process, known as 3-D printing, resembles the operation of ink-jet printers but, in this case, instead of ink the printer uses a solution of living cells. In the end, Atala's machine produced, layer by layer, a life-size kidney made of human cells, much as a personal 3-D printer can spit out, say, a plastic replacement part for a coffeemaker.

A straightforward and quick way to make organs would be a welcome development for the more than 105,000 Americans waiting for organ donations. But the printed kidney Atala demonstrated two years ago was not ready to implant. It lacked two crucial elements: working blood vessels and tubules for collecting urine. Without these or other internal channels, large organs such as the kidneys have no way to get crucial nutrients and oxygen to, or remove waste products from, the cells deep within their interiors, and those cells quickly die. Researchers have tried to print these hollow structures layer by cellular layer into the organ by leaving holes in the right spots on each level, but the method produced conduits that can collapse and seams that can rupture under pressure from the blood being pumped by the heart.

A team of scientists from the University of Pennsylvania and the Massachusetts Institute of Technology has come up with a sweet solution to the problem. Instead of printing an organ and its inner vessels all at once, they print a dissolvable sugar mold of the vessels and *then* build up the appropriate cells around the mold. Later, the mold is washed away, leaving behind the structurally sound passageways that are able to stand up to the varying blood pressure levels found in the body.

AN INSPIRING DESSERT

THE IDEA CAME to Jordan Miller (one of the lead researchers on the project and a postdoctoral fellow at Penn) in two stages. First, while visiting a display of preserved human cadavers and organs at a Body Worlds exhibit, he saw that preparators

had exposed the lacelike structure of a large organ's vessels by injecting silicone into the vasculature and then dissolving away the remaining organic tissue.

Creating a synthetic mold on which to build internal vessels might work, Miller surmised, except that the chemicals needed to dissolve the silicone would be toxic to the living cells that were to be added. The way around that problem hit him when, at a fancy restaurant, he was served a dessert with an elegant hard-sugar lattice. Why not create a mold for an organ's blood vessels and other chambers out of sugar, which could be washed away with water?

Miller and his colleagues modified an open-source 3-D printer called the RepRap to print a carefully proportioned mixture of sugars in filaments of various sizes from about one millimeter down to 100 microns in diameter.

The team used these filaments to create an idealized version of a vascular network and coated the resulting sugar framework in a bio-friendly polymer to prevent the sugar from dissolving too fast. Then the scientists encased the whole thing in a combination of extracellular matrix [see "The Super Glue Cure," on page 52] and endothelial cells of the kind that line blood vessels. Finally, the researchers eliminated the sugar with water, ending up with sturdy blood vessels made up of living cells.

Then it was the cells' turn. Just as they do in the body, they began remodeling the blood vessels in which they found themselves—giving the overall structure more strength and even creating tiny capillaries at the ends of larger vessels. By allowing the cells to fill in some of the details, says Christopher Chen, who runs the Tissue Microfabrication Lab at Penn, "we don't have to perfectly design the architecture." In essence, the body can take over the finer touches on a nearly complete organ, allowing it to become fully functional.

To date, Chen, Miller and their colleagues have created blocks of liver tissue that contain sugar-molded blood vessels and implanted them in rodents to show that they will integrate with an existing vascular system. These slivers of tissue cannot take the place of a whole organ, but it is easy to see how adding liver, kidney or pancreatic cells on a fully developed vascular network could one day lead to the 3-D printing of larger body parts.

Replanting the Brain's Forest

Neurodegenerative disorders devastate the brain, but doctors hope one day to replace lost cells

By Ferris Jabr

INSIDE THE HUMAN BRAIN, branching neurons grow beside, around and on top of one another like trees in a dense forest. Scientists used to think that any neurons that wilted and died from injury or disease were gone forever because the brain had no way to replace those cells. By the 1990s, however, most neuroscientists had accepted that the adult brain cultivates small gardens of stem cells that can turn into mature neurons.

Researchers are still trying to determine exactly how often these stem cells become new neurons and how well these differentiated cells survive and join established brain circuits. Some evidence suggests that the brain's neural stem cells help the organ heal itself in modest ways—helping to replace small populations of neurons that suffocated during a stroke, for example. But this minimal self-repair does not restore the millions of neurons lost to stroke, traumatic brain injury and neurodegenerative diseases such as Alzheimer's and Parkinson's.

If stem cell therapy works for Parkinson's, doctors might be able to treat a wider range of nervous system diseases.

Twenty years ago neurosurgeons tried to overcome the brain's limited regenerative ability by slicing up sheets of fetal brain tissue and grafting them onto a diseased brain to replace dead neurons with new ones. The resulting clinical trials were disappointing, but some investigators think they have now worked out how to make the treatment safer and more reliable. Instead of relying on fetal tissue, scientists can grow millions of young neurons from stem cells in the laboratory and inject the juvenile brain cells directly into patients' brains. Although few expect the therapy to be widely used for another decade or two, early studies toward that end have begun.

The most promising work so far focuses on Parkinson's, which seems to be particularly responsive to grafting. Parkinson's, which affects about 10 million people (including one million Americans) worldwide, results primarily from the death of dopamine-secreting neurons in the substantia nigra, a section of the midbrain important for controlling movement, among other functions. Symptoms include shaking, stiffness and difficulty walking.

In the early 1980s researchers harvested immature brain tissue from rat fetuses and transplanted it into the substantia nigra of rodents whose dopaminergic neurons had been killed to mimic Parkinson's. Despite the transplanted neurons surviving the procedure, they largely failed to form functional neural circuits. Usually, as the brain develops in the womb, neurons in the substantia

nigra extend branches to another region of the brain called the striatum, where they squirt out the neurotransmitter dopamine to communicate with striatal neurons. In the fetal brain, the distance between the substantia nigra and striatum is not that large; in an adult brain—even an adult rat's brain—the distance is considerably greater. In those early experiments, the transplanted neurons could not bridge the gap. In follow-up studies, researchers instead tried grafting the immature neurons directly into the striatum. It seemed to work. The cells survived, wove themselves into existing neural circuits and began to secrete dopamine.

In subsequent experiments with rodents and monkeys, such transplants have restored dopamine to nearly typical levels in the brain and improved motor functions—the animals do not quiver as much and gain better control of objects in their grasp. Researchers have speculated that the treatments work not only because the transplanted neurons release dopamine but also because they secrete substances called growth factors that protect and nurture dopamine-receptive cells in the striatum. Because the transplanted neurons are living cells that continuously produce, secrete and absorb neurotransmitters, they may balance dopamine levels in the brains of Parkinson's patients more effectively than pharmaceutical treatments, such as L-dopa.

BRAIN GROWTH
To replace brain cells lost to neurodegenerative disorders such as Parkinson's disease, some researchers are experimenting with grafts of fetal brain tissue and injections of young neurons grown from stem cells in the lab.

By the early 1990s four people with Parkinson's had received transplants of fetal brain tissue in Sweden—pioneering work that paved the way for two larger clinical trials of 40 and 34 people, respectively, in the U.S., funded by the National Institutes of Health. In both trials, half the patients received transplants, and half underwent sham surgery. The results were discouraging: treatment groups did no better than the sham groups, except for some patients younger than 60 in one of the trials.

Whereas many researchers viewed these trials as complete failures, others saw reasons to question the data and try again. First, transplants of fetal tissue are notoriously difficult to standardize—patients often receive tissue samples of varying quality from multiple donors. Second, Anders Björklund of Lund University and other researchers argued that the trials expected improvements too soon. Transplanted neurons are so immature that they will likely require several years to fully integrate themselves into the brain. A follow-up study to one of the NIH-funded trials found that two and four years after receiving grafts, some patients had improved.

Lorenz Studer of the Memorial Sloan-Kettering Cancer Center has focused on a different way of replacing cells lost to Parkinson's—a strategy that solves the issue of standardization. In the lab, he exposes embryonic stem cells to a series of molecules that mimic the kind of chemical signaling the cells would receive in the fetal brain, nudging them toward a specific stage of development equivalent to about two months in utero—just after their last cell division but before they have grown any long or intricate branches. Because he carefully guides their growth and development in the lab, he can generate millions of nearly identical young neurons for transplantation. Injecting undifferentiated embryonic stem cells into the brain—or any organ—risks the formation of tumors, because stem cells can grow uncontrollably; shepherding stem cells toward an adult form in the lab greatly reduces that risk. So far Studer has published promising results with rodents and monkeys—both sets of animals showed improved motor control—and he hopes to start clinical trials in humans in three to four years.

"This research addresses a broader issue: how to help the brain repair itself," Björklund says. "Parkinson's is a very good test bed for this new approach to therapy. If we can make stem cell therapy work for Parkinson's, this opens up the possibility of treating a wider spectrum of central nervous system damage and disease."

Learn more about regenerative medicine at ScientificAmerican.com/apr2013/regenerative-medicine

HIDDEN COSTS

Energy Lost from Mine to Car

The steps involved in mining and processing Canada's tar sands to produce oil offer an example of why unconventional fuels can be less attractive than traditional fuels, in terms of the amount of energy they yield versus how much is invested in producing them. First comes energy-intensive logging, digging, hauling, crushing, washing and heating of the sand-laden raw product to separate out the tarlike bitumen (*inner ring*). An on-site refinery called an upgrader must then cook the bitumen to turn it into regular crude oil, which is eventually transported by pipeline and sometimes tanker. Another method requires energy to create steam that melts the bitumen underground. Of course, all the operations require human labor (*second ring*). Distant refineries consume still more energy to turn the crude into gasoline and other fuels. Cleanup afterward includes water purification and land reclamation, both of which require yet more energy. Traditional drilling, extracting and refining conventional crude oil demand much less energy investment.

Illustration by Oliver Munday

Mason Inman is a freelance journalist in Oakland, Calif. He is now writing a biography of geologist M. King Hubbert, who is often called the "father of peak oil."

ENERGY

THE TRUE COST OF *Fossil Fuels*

As oil becomes more expensive, determining where to invest energy to get energy is increasingly important

By Mason Inman

CANADA'S TAR SAND PROJECTS SPRAWL ACROSS 600 SQUARE KILOMETERS OF NORTHEASTERN Alberta. Prime Minister Stephen Harper has called the industrial effort to extract oil from the deposits "an enterprise of epic proportions, akin to the building of the pyramids or China's Great Wall. Only bigger."

As traditional oil and natural gas reserves become increasingly difficult to find, and as demand rises, energy companies are turning to unconventional resources that, like the tar sands, are harder and more costly to access. Production of tar sands–based oil, for instance, has tripled over the past decade, reaching 1.6 million barrels a day in 2011.

Given that unconventional sources are needed, which ones make the most sense to extract? It takes an unusually high amount of energy to get at them—whether it be tar sands, natural gas from hydraulic fracturing shale, or old oil deposits that can be flooded with steam to scour out more petroleum. To help compare fuel sources with a common metric, ecologist Charles A. S. Hall of the S.U.N.Y. College of Environmental Science and Forestry has created a measure called the "energy return on investment" (EROI). It indicates the energy that fuels provide per unit of energy spent—a ratio of energy obtained. A higher EROI means more energy is available to put to work. On the opposite page and on the ones that follow, I examine the inputs and outputs of various fuel sources to explain their EROIs.

"Everywhere you look, the EROI is declining," Hall says of oil and gas. His modeling suggests that a modern economy requires liquid fuel with an EROI of at least five; as the EROI decreases, society spends so much money on energy production that the costs eat into funds that could be spent elsewhere, whether on education, health care or entertainment.

By that measure, few options in the transportation sector are appealing [*see top illustration on next two pages*]. Yet low-EROI fuels are increasingly needed to meet ever higher demand, according to the International Energy Agency (IEA). Already, the IEA warns, oil prices are in the "danger zone," threatening economic growth. The electric power industry enjoys better EROIs [*see bottom illustration on next two pages*] because of access to more abundant resources.

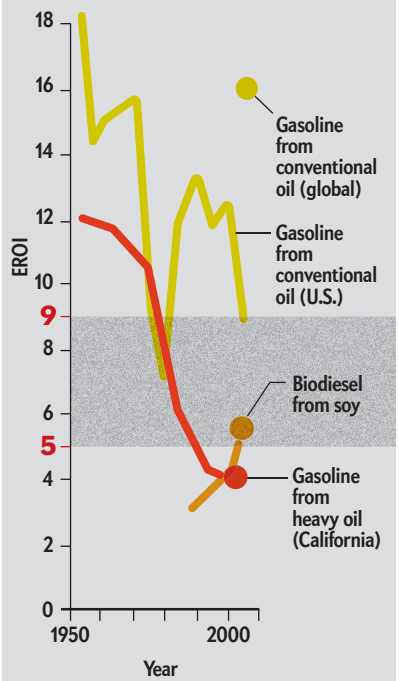
The EROI measure does not evaluate all the benefits and drawbacks of a fuel; notably, it does not address the environmental cost of greenhouse gas emissions or supply problems, such as the intermittence of wind or of solar power. Nevertheless, the EROI reveals how much energy to expect from a given source. It can also highlight how efforts to cut pollution—such as capturing carbon dioxide from coal-fired power plants—can drastically alter a fuel's affordability. By measuring the energy in versus the energy out, investment can be guided to the sources that most effectively keep the economy humming and that also can help build a sustainable future.

The Decline of Cheap Energy

Many experts say that high-quality fossil fuels that are cheap to extract are dwindling, forcing the world to turn to energy sources that are more costly to produce. This situation is revealed by calculating EROI—the energy obtained per unit of energy spent to obtain it. Conventional oil has a much more favorable EROI than other sources of liquid fuel (*chart at top right*), but its score is declining steadily (*graph below*). Conventional sources of electricity also have high EROIs (*chart at bottom right*), which can pay off handsomely when used for transportation (*chart at far right*). "The age of cheap energy is over," said Nobuo Tanaka in 2011, when he was the International Energy Agency's executive director.

Oil's Advantage Drops

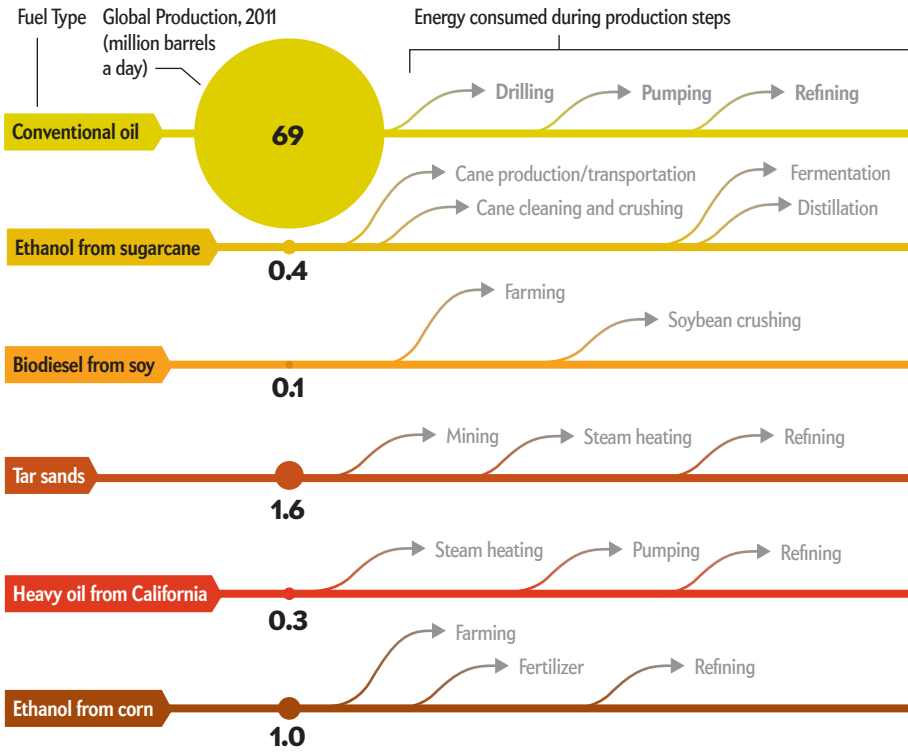
A modern economy requires fuels that have an EROI of at least five. For decades oil from conventional deposits soared above that threshold, but it is now dropping. Substitute sources such as heavy oil (thicker petroleum composed of longer hydrocarbon molecules) are more energy-intensive to produce, so they have lower EROIs. But alternative fuels, such as diesel made from soybeans, offer some hope.



DATA SOURCES: INTERNATIONAL ENERGY AGENCY; U.S. ENERGY INFORMATION ADMINISTRATION; U.S. DEPARTMENT OF AGRICULTURE; STUDIES BY CHARLES A. S. HALL ET AL. AND BY OTHER RESEARCHERS (*complete list of sources online at ScientificAmerican.com/apr2013/eroi*)

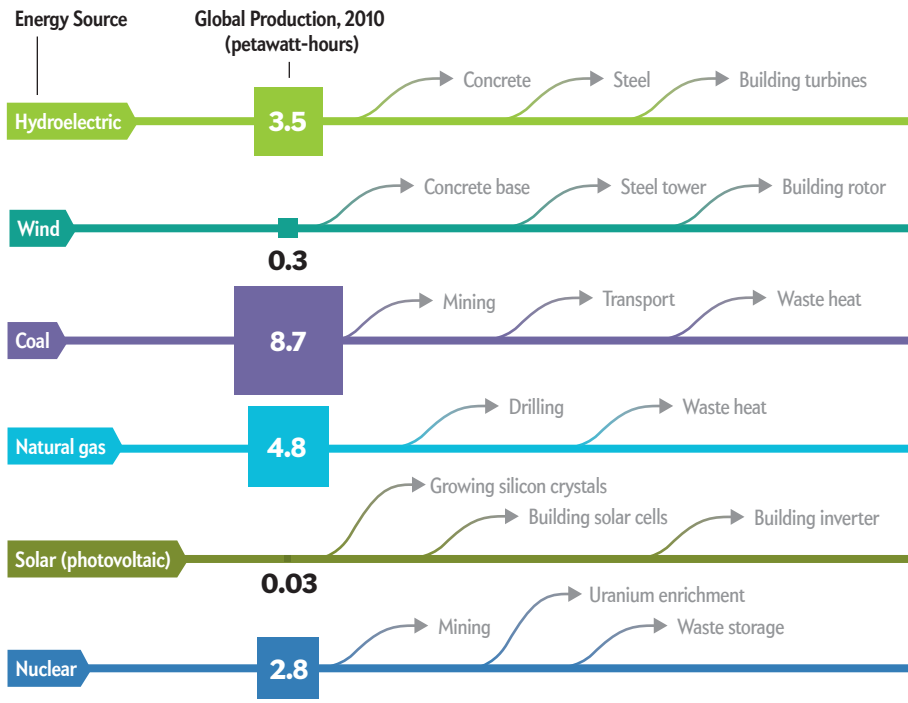
LIQUID FUELS: Crude Oil Gives the Best Energy Return—Today

Each raw material has to be extracted—from oil reservoirs or vegetation—and refined into gasoline or other fuels. Each step lowers the EROI. Values are recent industry averages or from typical installations.

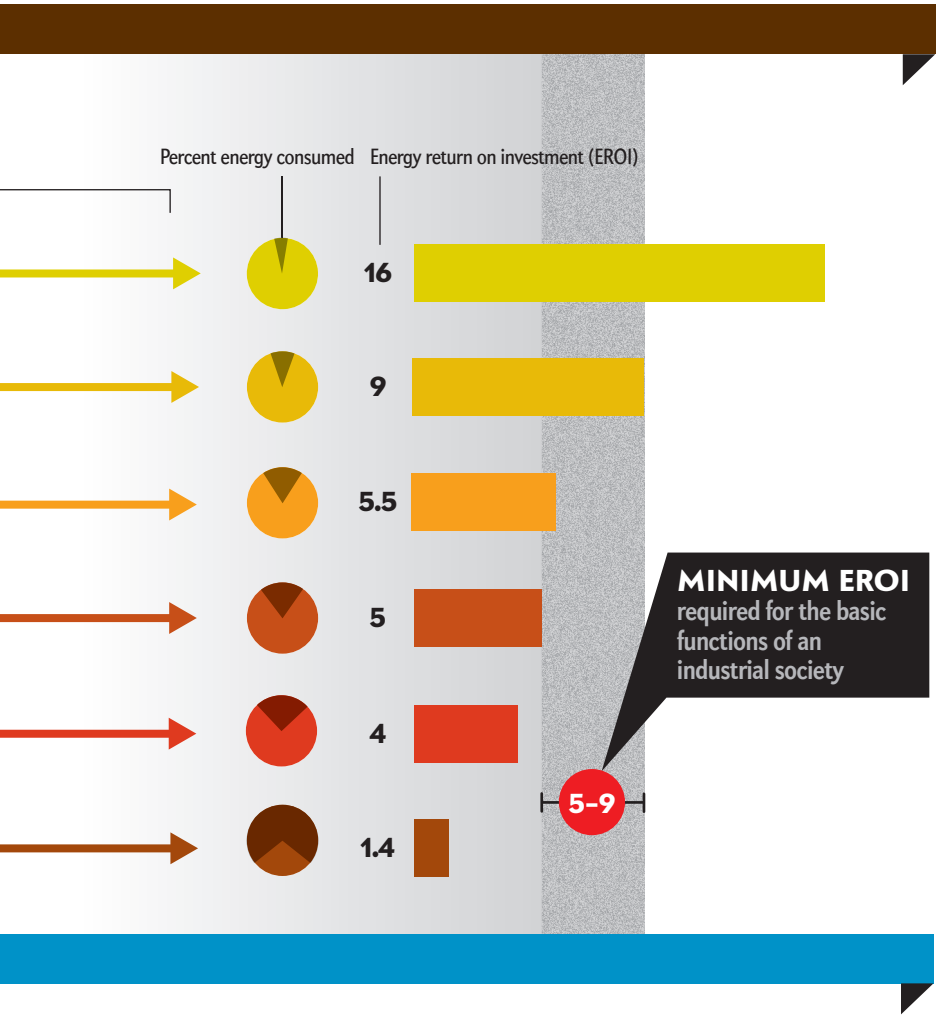


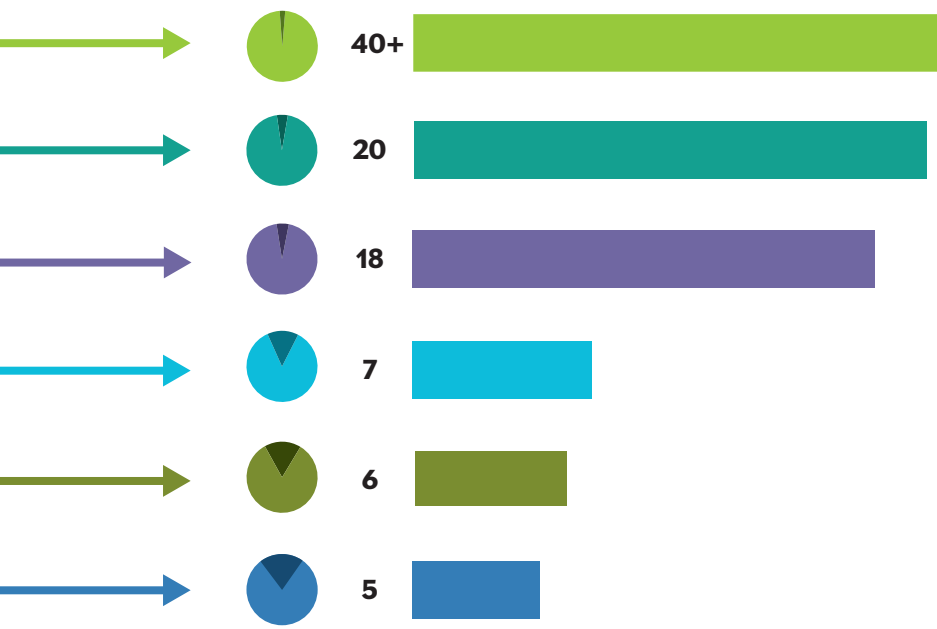
ELECTRIC POWER: Renewables Are Competitive with Fossil Fuels

Sources of electricity span a wide range of EROIs. Values are recent industry averages or from typical installations. Renewables do not include energy storage.



Graphic by Jen Christiansen

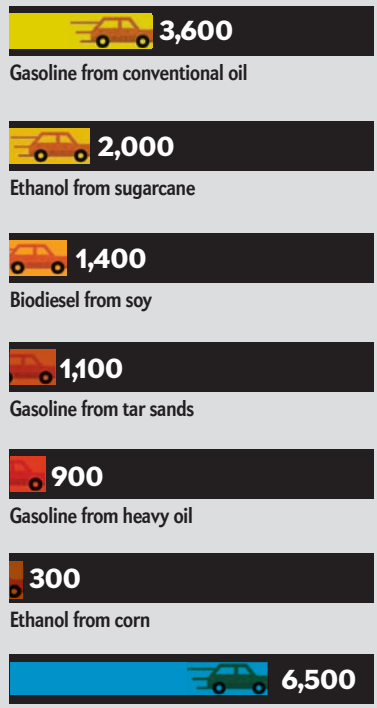




Mileage Return on Investment: Electricity Wins

Transportation fuels are not created equal. A car will go farthest on energy invested in generating electricity, then on conventional gasoline, followed by ethanol made from sugarcane. The miles traveled are based on the energy required to make each fuel, as well as its energy density (for example, ethanol's energy density is roughly 67 percent of gasoline's). For electric cars, this value does include electricity transmission, but not manufacturing batteries.

Distance Driven on One Gigajoule of Energy Invested in Fuel Production (miles)



MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE

For more on the calculations behind EROI and a Q&A with Charles A. S. Hall, go to ScientificAmerican.com/apr2013/eroi

CHILD DEVELOPMENT

Anguish of the Abandoned Child

The plight of orphaned Romanian children reveals the psychic and physical scars from first years spent without a loving, responsive caregiver

By Charles A. Nelson III, Nathan A. Fox and Charles H. Zeanah, Jr.

IN BRIEF

Communist dictator Nicolae Ceauşescu banned birth control and abortion in 1966 to increase Romania's population. Overwhelmed, parents left children by the thousands in state institutions.

Romanian officials, in trying later to make up for these abuses, agreed to a study by U.S. investigators to determine the inimical effects of early life in an orphanage on the still large numbers of institutionalized children.

A first-ever randomized trial comparing the emotional and physical well-being of institutionalized children with those placed in a foster home began in Bucharest in 2000.

Life in an orphanage took its toll. The study found that children who passed the first two years in an institution had a lower IQ and attenuated brain activity compared with foster children or those never institutionalized.

ORPHANS:
Two Romanian boys occupied a urine-soaked iron crib in a state-run institution in 1990.

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Nathan A. Fox is Distinguished University Professor in the department of human development and quantitative methodology at the University of Maryland, College Park.

Charles H. Zeanah, Jr., is professor of psychiatry and clinical pediatrics at Tulane University and executive director of the university's Institute of Infant and Early Childhood Mental Health.

In a misguided effort to enhance economic productivity, Nicolae Ceauşescu decreed in 1966 that Romania would develop its "human capital" via a government-enforced mandate to increase the country's population. Ceauşescu, Romania's leader from 1965 to 1989, banned contraception and abortions and imposed a "celibacy tax" on families that had fewer than five children. State doctors—the menstrual police—conducted gynecologic examinations in the workplace of women of childbearing age to see whether they were producing sufficient offspring. The birth rate initially skyrocketed. Yet because families were too poor to keep their children, they abandoned many of them to large state-run institutions. By 1989 this social experiment led to more than 170,000 children living in these facilities.

The Romanian revolution of 1989 deposed Ceauşescu, and over the next 10 years his successors made a series of halting attempts to undo the damage. The "orphan problem" Ceauşescu left behind was enormous and did not disappear for many years. The country remained impoverished, and the rate of child abandonment did not change appreciably at least through 2005. A decade after Ceauşescu had been removed from power, some government officials could still be heard saying that the state did a better job than families in bringing up abandoned children and that those confined in institutions were, by definition, "defective"—a view grounded in the Soviet-inspired system of educating the disabled, dubbed "defectology."

Even after the 1989 revolution, families still felt free to abandon an unwanted infant to a state-run institution. Social scientists had long suspected that early life in an orphanage could have adverse consequences. A number of mostly small, descriptive studies that lacked control groups were conducted from the 1940s to the 1960s in the West that compared children in orphanages with those in foster care and showed that life in an institution did not come close to matching the care of a parent—even if that parent was not the natural mother or father. One issue with these studies was the possibility of "selection bias": children removed from institutions and placed into adoptive or foster homes might be less impaired, whereas the ones who remained in the institution were more disabled. The only way to counter any bias would require the unprecedented step of randomly placing a group of abandoned children into either an institution or a foster home.

Understanding the effects of life in an institution on children's early development is important because of the immensity of the orphan problem worldwide (an orphan is defined here as an abandoned child or one whose parents have died). War, disease, poverty and sometimes government policies have stranded at least eight million children worldwide in state-run facilities. Often these children live in highly structured but hopelessly bleak environments, where typically one adult oversees 12 to 15 children. Research is still lacking to gain a full understanding of what happens to children who spend their first years in such deprived circumstances.

In 1999, when we approached Cristian Tabacaru, then secretary of state for Romania's National Authority for Child Protection, he encouraged us to conduct a study on institutionalized children because he wanted data to address the question of whether to develop alternative forms of care for the 100,000 Romanian children then living in state institutions. Yet Tabacaru faced stiff resistance from some government officials, who believed for decades that children received a better upbringing in institutions than in foster care. The problem was exacerbated because some government agencies' budgets were funded, in part, by their role in making institutional care arrangements. Faced with these challenges, Tabacaru thought that scientific evidence about putative advantages of foster care for young children over state institutions would make a convincing case for reform, and so he invited us to go ahead with a study.

Infancy in an Institution

With the assistance of some officials within the Romanian government and especially with help from others who worked for SERA

PRECEDING PAGES: TARO YAMASAKI *Getty Images*

PLACE TO CALL HOME for these Romanian foster care children was essential for healthy development.

Romania (a nongovernmental organization), we implemented a study to ascertain the effects on a child's brain and behavior of living in a state institution and whether foster care could ameliorate the effects of being reared in conditions that run counter to what we know about the needs of young children. The Bucharest Early Intervention Project was launched in 2000, in cooperation with the Romanian government, in part to provide answers that might rectify the aftereffects of previous policies. The unfortunate legacy of Ceauşescu's tenure provided a chance to examine, with greater scientific rigor than any previous study, the effects of institutionalized care on the neurological and emotional development of infants and young children. The study was the first-ever randomized controlled study that compared a group of infants placed in foster care with another raised in institutions, providing a level of experimental precision that had been hitherto unavailable.

We recruited, from all six institutions for infants and young children in Bucharest, a group of 136 whom we considered to be free of neurological, genetic and other birth defects based on pediatric exams conducted by a member of the study team. All had been abandoned to institutions in the first weeks or months of life. When the study began, they were, on average, 22 months old—the range of ages was from six to 31 months.

Immediately after a series of baseline physical and psychological assessments, half the children were randomly assigned to a foster care intervention our team developed, maintained and financed. The other half remained in an institution—what we called the "care as usual" group. We also recruited a third group of typically developing children who lived with their families in Bucharest and had never been institutionalized. These three groups of children have been studied for more than 10 years. Because the children were randomly assigned to foster care or to remain in an institution, unlike previous studies, it was possible to show that any differences in development or behavior between the two groups could be attributed to where they were reared.

Because there was virtually no foster care available for abandoned children in Bucharest when we started, we were in the unique position of having to build our own network. After extensive advertising and background checks, we eventually recruited 53 families to foster 68 children (we kept siblings together).

Of course, many ethical issues were involved in conducting a controlled scientific study of young children, a trial in which only half the participants were initially removed from institutions. The design compared the standard intervention for abandoned children—institutional rearing—with foster care, an intervention that had never been available to these children. Ethical protections put in place included oversight by multiple Romanian and U.S.-based institutions, implementation of "minimal risk" measures (all used routinely with young children), and noninterference with government decisions about changes in placement when children were adopted, returned to biological parents or later placed in government-sponsored foster care that at the outset did not exist.

No child was moved back from foster care to an institution at the end of the study. As soon as the early results became available, we communicated our findings to the Romanian government at a news conference.

To ensure high-quality foster care, we designed the program to incorporate regular involvement of a social work team and provided modest subsidies to families for child-related expenses. All foster parents had to be licensed, and they were paid a salary as well as a subsidy. They received training and were encouraged to make a full psychological commitment to their foster children.

SENSITIVE PERIODS

THE STUDY SET ABOUT TO EXPLORE the premise that early experience often exerts a particularly strong influence in shaping the immature brain. For some behaviors, neural connections form

COURTESY OF MIKE CARROLL

in early years in response to environmental influences during windows of time, called sensitive periods. A child who listens to spoken language or simply looks around receives aural and visual inputs that shape neural connections during specific periods of development. The results of the study supported this initial premise of a sensitive period: the difference between an early life spent in an institution compared with foster care was dramatic. At 30, 40 and 52 months, the average IQ of the institutionalized group was in the low to middle 70s, whereas it was about 10 points higher for children in foster care. Not surprisingly, IQ was about 100, the standard average, for the group that had never been institutionalized. We also discovered a sensitive period when a child was able to achieve a maximum gain in IQ: a boy or girl placed in a home before roughly two years of age had a significantly higher IQ than one put there after that age.

The findings clearly demonstrate the devastating impact on mind and brain of spending the first two years of life within the impersonal confines of an institution. The Romanian children living in institutions provide the best evidence to date that the initial two years of life constitute a sensitive period in which a child must receive intimate emotional and physical contact or else find personal development stymied.

Infants learn from experience to seek comfort, support and protection from their significant caregivers, whether those individuals are natural or foster parents—and so we decided to measure attachment. Only extreme conditions that limit opportunities for a child to form attachments can interfere with a process that is a foundation for normal social development. When we measured this variable in the institutionalized children, we found that the overwhelming majority displayed incompletely formed and aberrant relationships with their caregivers.

When the children were 42 months of age, we made another assessment and found that the children placed in foster care displayed dramatic improvements in making emotional attachments. Almost half had established secure relationships with another person, whereas only 18 percent of the institutionalized children had done so. In the community children, those never institutionalized, 65 percent were securely attached. Children placed into foster care before the end of the 24-month sensitive period were more likely to form secure attachments compared with children placed there after that threshold.

These numbers are more than just statistical disparities that separate the institutionalized and foster groups. They translate into very real experiences of both anguish and hope. Sebastian (none of the children's names in this article are real), now 12, has spent virtually his entire life in an orphanage and has seen his IQ drop 20 points to a subpar 64 since he was tested during his fifth year. A youth who may have never formed an attachment with anyone, Sebastian drinks alcohol and displays other risk-prone behaviors. During an interview with us, he became irritable and erupted with flashes of anger.

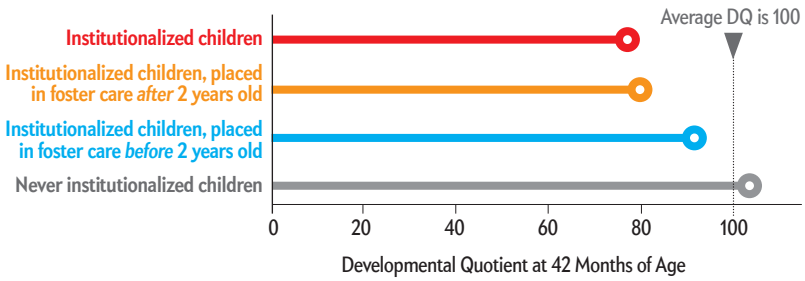
Bogdan, also 12, illustrates the difference that receiving individualized attention from an adult makes. He was abandoned at birth and lived in a maternity ward until two months of age, after which he lived in an institution for nine months.

FINDINGS

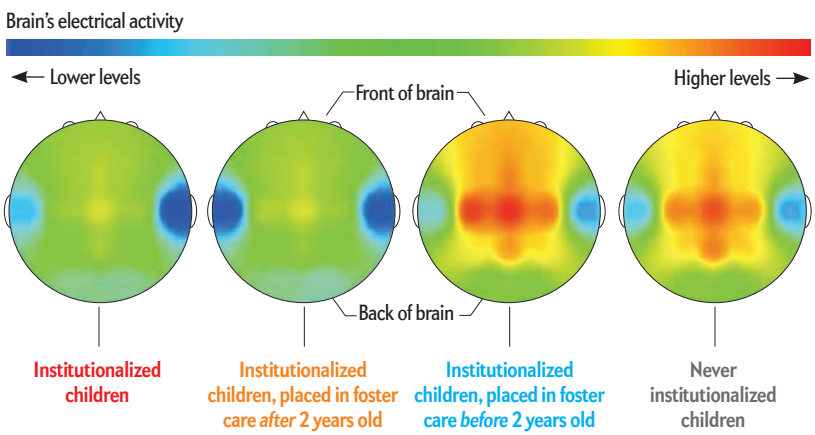
Someone to Watch over You

The tragedy of Communist leader Nicolae Ceauşescu's policy to increase the national birth rate led to as many as 100,000 abandoned children in Romania in 1999—and an unprecedented opportunity to assess the psychological and neurological impact of early life in a state institution. An experiment, undertaken under strict ethical supervision, tracked the fate of children in an institution against those placed in foster care and others who were never institutionalized. Children who went to a foster home during the sensitive period up to 24 months of age fared better than those who remained in an institution when tested later (at 42 months) for developmental quotient (DQ), a measure of intelligence equivalent to IQ, and for brain electrical activity, as assessed by electroencephalograms (EEGs). Entering foster care after two years produced EEGs that resembled those of institutionalized children.

Early Entry into Foster Care Resulted in Higher Average Intelligence ...



... and Brain Functioning at Age 8 Almost Matched That of Never Institutionalized Children



SOURCES: CHARLES A. NELSON (*DQ data*); "TIMING OF INTERVENTION AFFECTS BRAIN ELECTRICAL ACTIVITY IN CHILDREN EXPOSED TO SEVERE PSYCHOSOCIAL NEGLECT" BY K. E. VANDERWERT, P. J. MARSHALL, C. A. NELSON III, C. H. ZEANAH and N. A. FOX, IN *PLOS ONE*, VOL. 5, NO. 7, JULY 1, 2010 (*EEGs*)

He was then recruited into the project and randomized to the foster care group, where he was placed in the family of a single mother and her adolescent daughter. Bogdan started to catch up quickly and managed to overcome mild developmental delays within months. Although he had some behavioral problems, project staff members worked with the family, and by his fifth birthday the foster mother had decided to adopt him. At age 12, Bogdan's IQ continues to score at an above-average level. He attends one of the best public schools in Bucharest and has the highest grades in his class.

Because children raised in institutions did not appear to receive much personal attention, we were interested in whether a paucity of language exposure would have any effect on them. We observed delays in language development, and if children arrived in foster care before they reached approximately 15 or 16 months, their language was normal, but the later children were placed, the further behind they fell.

We also compared the prevalence of mental health problems among any children who had ever been institutionalized with those who had not. We found that 53 percent of the children who had ever lived in an institution had received a psychiatric diagnosis by the age of four and a half, compared with 20 percent of the group who had never been institutionalized. In fact, 62 percent of the institutionalized children approaching the age of five had diagnoses, ranging from anxiety disorders—44 percent—to attention-deficit hyperactivity disorder (ADHD)—23 percent.

Foster care had a major influence on the level of anxiety and depression—reducing their incidence by half—but did not affect behavioral diagnoses (ADHD and conduct disorder). We could not detect any sensitive period for mental health. Yet relationships were important for assuring good mental health. When we explored the mechanism to explain reduced emotional disorders such as depression, we found that the more secure the attachment between a child and foster parent, the greater probability that the child's symptoms would diminish.

We also wanted to know whether first years in a foster home affected brain development differently than living in an institution. An assessment of brain activity using electroencephalography (EEG)—which records electrical signals—showed that infants living in institutions had significant reductions in one component of EEG activity and a heightened level in another (lower alpha and higher theta waves), a pattern that may reflect delayed brain maturation. When we assessed the children at the eight-year mark, we again recorded EEG scans. We could then see that the pattern of electrical activity in children placed in foster care before two years of age could not be distinguished from that of those who had never passed time in an institution. Children taken out of an orphanage after two years and those who never left showed a less mature pattern of brain activity.

The noticeable decrease in EEG activity among the institutionalized children was perplexing. To interpret this observation, we turned to data from magnetic resonance imaging, which can visualize brain structures. Here we observed that the institutionalized children showed a large reduction in the volume of both gray matter (neurons and other brain cells) and white matter (the insulating substance covering neurons' wirelike extensions).

On the whole, all the children who were institutionalized had smaller brain volumes. Placing children in foster care at any age had no effect on increasing the amount of gray matter—the foster care group showed levels of gray matter comparable to those of the institutionalized children. Yet the foster care children showed more white matter volume than the institutionalized group, which may account for the changes in EEG activity.

To further examine the biological toll of early institutionalization, we focused attention on a crucial area of the genome. Telomeres, regions at the ends of chromosomes that provide protection from the stresses of cell division, are shorter in adults who undergo extreme psychological stresses than those who escape this duress. Shorter telomeres may even be a mark of accelerated cellular aging. When we examined telomere length in the children in our study, we observed that, on the whole, those who had spent any time in an institution had shorter telomeres than those who had not.

LESSONS FOR ALL

THE BUCHAREST EARLY INTERVENTION PROJECT has demonstrated the profound effects early experience has on brain development. Foster care did not completely remedy the profound developmental abnormalities linked to institutional rearing, but it did mostly shift a child's development toward a healthier trajectory.

The identification of sensitive periods—in which recovery from deprivation occurs the earlier the child begins to experience a more favorable living environment—may be one of the most significant findings from our project. This observation has implications beyond the millions of children living in institutions, extending to additional millions of maltreated children whose care is being overseen by child-protection authorities. We caution readers, however, not to make unwarranted assumptions that two years can be rigidly defined as a sensitive period for development. Yet the evidence suggests that the earlier children are cared for by stable, emotionally invested parents, the better their chances for a more normal development trajectory.

We are continuing to follow these children into adolescence to see if there are "sleeper effects"—that is, significant behavioral or neurological differences that appear only later in youth or even adulthood. Further, we will determine whether the effects of a sensitive period we observed at younger ages will still be observed as children enter adolescence. If they are, they will reinforce a growing body of literature that speaks to the role of early life experiences in shaping development across one's life span. This insight, in turn, may exert pressure on governments throughout the world to pay more attention to the toll that early adversity and institutionalization take on the capacity of a maturing child to traverse the emotional hazards of adolescence and acquire the needed resiliency to cope with the travails of adult life. SA

MORE TO EXPLORE

Cognitive Recovery in Socially Deprived Young Children: The Bucharest Early Intervention Project. Charles A. Nelson III et al. in *Science*, Vol. 318, pages 1937–1940; December 21, 2007.

Effects of Early Intervention and the Moderating Effects of Brain Activity on Institutionalized Children's Social Skills at Age 8. Alisa N. Almas et al. in *Proceedings of the National Academy of Sciences USA*, Vol. 109, Supplement No. 2, pages 17,228–17,231; October, 16, 2012.

SCIENTIFIC AMERICAN ONLINE

For a video that details more about the importance of early-life caregiving, visit ScientificAmerican.com/apr2013/orphans

ALL ABOARD:
SpaceX's Falcon 9 rocket launched the Dragon spacecraft on its inaugural orbital mission in 2010, becoming the first commercial company to send a spacecraft to orbit and return it safely to Earth.

SPACE EXPLORATION

THE LOW-COST TICKET TO SPACE

Private spaceflights aren't just for well-heeled tourists. The nascent commercial space industry is poised to revolutionize research as well

By S. Alan Stern

IN BRIEF

Researchers who require access to space have long been frustrated by infrequent launch rates—an inevitable consequence of expensive launches.

But new privately owned space launch companies are heralding an era of far cheaper and more frequent flights to space.

Although many of the companies were founded to send tourists into space, researchers will be able to purchase room on the flights for their experiments for a cost that is far lower than their current options.

Even researchers who would like to send experiments to the moon or on extended journeys in orbit around Earth are likely to benefit from companies now developing lunar landers and private space stations.

S. Alan Stern is a planetary scientist and explorer based at Southwest Research Institute in Boulder, Colo. He is the leader of the New Horizons mission to Pluto and the Kuiper belt and has consulted for multiple private spaceflight companies. He formerly led all of NASA's space and Earth science programs.

One of the most vexing problems in space

research is that so little has changed in 50 years about the way we get to space. Consequently, space access remains both expensive and rare. It has still not reached the stage where scientists can themselves routinely travel there to conduct research, unlike oceanographers, who routinely reach the deep ocean, or geophysicists, who venture to the poles.

All this is poised to change. The advent of for-profit commercial spaceflight—most recently highlighted by the successful launches of the Dragon space cargo capsule, built and operated by SpaceX, to the International Space Station (ISS)—will likely transform space research. Scientists will enjoy lower launch costs, far more frequent access to space and the opportunity to personally run their experiments in orbit. These advances will not only help the big space research enterprises at NASA and the Japanese and the European space agencies, they will also probably make space access affordable to a broad, global base of nations, academic institutions and corporations.

I first became interested in the potential of commercial spaceflight when I served as NASA's associate administrator in charge of all space and Earth science studies. Since then, I have advised commercial space companies, served as chief scientist for two Google Lunar X PRIZE teams, and purchased commercial human research spaceflights through my home institution, the Southwest Research Institute based in San Antonio, Tex. I have seen the promise of commercial spaceflight grow firsthand.

A rich variety of commercial space systems coming online in the next few years will offer important new capabilities of interest to space researchers—scientists who, ever since the post–World War II days of converting captured German V-2 rockets into research platforms, have been clever opportunists looking for better ways to accomplish their work. Although some plans now in the works may falter, others will surely succeed. And with the well-known present-day environment of tightening budgets, cost overruns and a long-standing stagnation in space access, that success cannot happen fast enough.

I believe it is a fair bet that the 2010s and 2020s may be just as pivotal to how we explore space as the 1950s and 1960s were. Indeed, we are already witnessing a revolution in the making. From the suborbital flights that are commonly touted as "tourist" ventures (but that will also offer scientists a seat) to orbital trips to the ISS and beyond, the coming years will reshape our relation to the still mysterious world just above Earth.

THE SUBORBITAL FUTURE

ONE OF NASA'S most productive—and unfortunately perhaps least known—spaceflight efforts has been its suborbital program. In place for decades, this program launches one or two brief space missions every month onboard throwaway unmanned rockets, giving researchers the opportunity to put their instruments in space for a few minutes at a time. Despite the brevity of these flights, suborbital missions have produced key scientific results in solar physics, supernova studies, upper atmospheric science, astrophysics and comet research. In addition, they have proved invaluable for testing new spacecraft and sensor technologies before they are committed to billion-dollar missions, and they have trained countless space experimentalists, including some of the most accomplished astronomers, atmospheric scientists and planetary mission leaders in the U.S.

Despite repeated calls by the scientific community over the past 20 years for steep increases in flight frequencies, however, NASA's suborbital program launch rate has stayed frustratingly

PRECEDING PAGES: COURTESY OF SPACEX

SUPPLY CHAIN: SpaceX's Dragon spacecraft delivered supplies to the International Space Station last spring.

low. The reasons why are many, but they center on expense. The average cost to conduct one of these missions is about $2.5 million, which makes significantly higher rates impossible within NASA's suborbital program budget.

Yet the advent of new, reusable suborbital vehicles, built by commercial companies such as XCOR Aerospace, Virgin Galactic, Armadillo Aerospace, Masten Space Systems and Blue Origin, offers breakthrough capabilities that are expected to radically improve both the pace and the productivity of suborbital research.

How is this possible? First, by flying reusable rather than disposable launchers, these companies can dramatically lower flight costs and increase launch rates. This potent pair of advances will most likely affect space research the way that the PC revolution changed computing—creating an access revolution.

NASA now flies roughly 20 to 25 suborbital launches a year. Suborbital flight provider Virgin Galactic expects its very first vehicle to eventually fly once every day. And each flight will be capable of carrying six payload racks or six researchers (or a mix thereof). This one company could provide about 2,000 opportunities to experiment every year.

Virgin Galactic is not alone in this new market. XCOR Aerospace, one of Virgin's toughest rivals, expects to launch four times a day with each of its reusable vehicles, several of which have already been leased to countries that include South Korea and Curaçao. Just imagine how fast research fields could advance with flights this frequent. Life scientists, for example, could take hundreds of astronaut zero-gravity data sets each year, up from the handful of such studies we currently get.

Of course, high flight rates alone cannot a revolution make. The other key attribute of these reusable systems is their lower cost. Virgin Galactic plans to sell a 200-pound payload or research position on a suborbital mission for $200,000—which is about 10 times less expensive than a conventional-sounding rocket mission launch. XCOR's quoted price, like Armadillo Aerospace's, is nearer to just $100,000.

The reusable rocket revolution will also make possible new kinds of science. For example, with frequent access to the scientifically crucial high-altitude atmospheric region researchers call the "ignorosphere"—too high to reach with aircraft and balloons and too low for satellites to dip down to without tumbling back to Earth—scientists will be able to study many atmospheric phenomena, including mysterious high-altitude electrical bursts known as red sprites and blue jets.

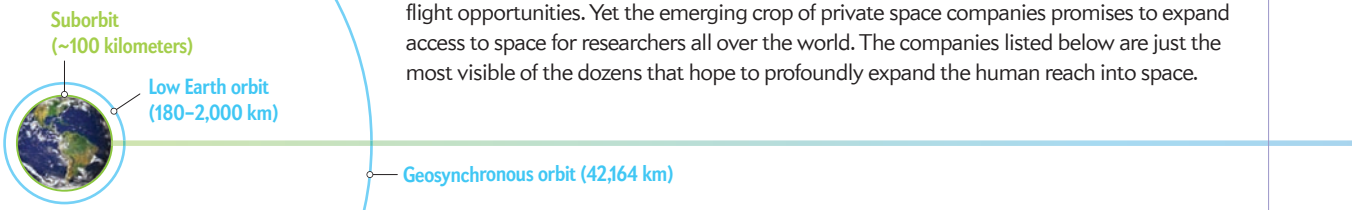
These new vehicles also offer huge advantages in terms of their revolutionary capability to fly researchers with their payloads. For the first time since the dawn of the space age, space research might soon just enter the realm every other research field has long enjoyed: a laboratory environment where scientists can conduct their own experiments, on the spot, without the need for robotics.

Although much of this may sound like science fiction, researchers from some institutions are already making flight reservations for themselves and their experiments. By the middle of this decade, next-generation suborbital technology may be blossoming in the same way sounding rocket research did in 1950s—going from rare to routine. Would that alone be a dramatic

COURTESY OF SPACEX

Who Will Power the Space Research Revolution?

Getting to space is hard, and space research has long been hindered by expensive and rare flight opportunities. Yet the emerging crop of private space companies promises to expand access to space for researchers all over the world. The companies listed below are just the most visible of the dozens that hope to profoundly expand the human reach into space.



	SUBORBITAL	ORBITAL	MOON	EXTENDED STAY
MAIN COMPANIES	Armadillo Aerospace, Blue Origin, Virgin Galactic, XCOR Aerospace	SpaceX	Astrobotic Technology, Moon Express	Bigelow Aerospace, Excalibur Almaz
ADVANTAGES OVER TRADITIONAL APPROACH	Reusable launchers allow for rapid turnaround between flights, as well as a lower cost per flight; researchers will also be able to routinely accompany their experiments into space	SpaceX designed its Falcon rockets and Dragon capsules from scratch with an eye to simplicity and reliability; flights on the Falcon 9 cost half that of a similar ride provided by traditional contractors	Small robotic lunar landers will be the first spacecraft to make a soft landing on the moon since the Soviet Luna 24 mission in 1976; plans are under way to probe for water ice near the moon's south pole	Bigelow's inflatable stations are relatively light, making them easier to launch than traditional hard-bodied stations such as the International Space Station (ISS); they can also expand to volumes larger than rockets can carry
CURRENT STATUS	The first test flights are under way now, with the first passenger flights expected as early as next year; Virgin Galactic recently announced an orbital rocket launch program to begin in 2015	The Falcon 9 rocket has already delivered a Dragon capsule to resupply the ISS, the first of at least 12 such flights	The Google Lunar X PRIZE will award the first team to land a robot on the moon and send video back to Earth; Moon Express, one of the leading teams, plans to launch its mission by 2015	Bigelow began testing prototype stations in low Earth orbit in 2006; NASA recently announced it would attach a Bigelow module to the ISS in 2015; the first orbital outpost is planned for 2016

change? Yes, but these flights are only the first of several emerging commercial space capabilities that have relevance to the space research community.

INEXPENSIVE NEW WAYS TO REACH ORBIT

IN THE U.S., the launch vehicles that have historically been used for most of NASA's orbital science missions—the Pegasus, Atlas and Delta rockets—have each more than doubled in cost since the late 1990s. It used to cost about $15 million to launch a small science mission onboard a Pegasus rocket; it now costs more than $40 million. And the price of high-end rockets that can carry the largest payloads—so-called heavy lifters such as the Atlas V—has gone from $150 million to $350 million or so.

With space science budgets squeezed between funding cuts and cost overruns, science program managers at NASA could find less expensive commercial launch entrants to be a godsend. For example, consider the Falcon launcher line created by SpaceX. The company conceived, designed, developed, tested and made operational its Falcon launcher line for less money than the government took to build just the launch tower for its now defunct Ares rocket. SpaceX currently offers the Falcon 9 for about $65 million—about half what its medium-lift Delta II competitor costs. And by 2014 SpaceX is planning to field a much larger Falcon called the Falcon Heavy, or FH. The FH will be able to lift about twice what the largest Atlas and Delta rockets can but for only $100 million, less than a third of its competitors' price.

Historically, NASA has launched between three and five orbital science missions a year. Sending just half these missions on a Falcon Heavy would save between $2 billion and $3 billion over five years. Those savings are enough to field several new Discovery-class missions to another planet or nearly 10 Small Explorer missions used for astronomy and solar physics. They are even enough to fund a new flagship Mars rover akin to Curiosity.

Another cost-saving option that commercial space companies are pioneering is the ability to piggyback scientific payloads on commercial flights. For example, each of the 72 space-

NASA (*Earth and moon*)

craft in the second-generation Iridium communications satellite constellation offers space to paying customers. The host mission provides the launch and satellite costs, and the science instrument pays only a small fraction of that. Currently this "hosted payload" concept remains a boutique market. It works only when scientific instruments are able to fit onboard communication satellites and operate from their specialized orbits, and it is clearly not useful for large telescopes and other missions that require their own dedicated satellite. Yet it creates opportunities to launch modest payloads for tens of millions of dollars instead of the hundreds of millions it now takes to launch and operate a satellite mission.

TOWARD THE MOON AND MARS

THESE PIGGYBACKED PAYLOADS could soon bring scientific instruments well beyond Earth orbit. More than two dozen teams from Europe, North America, Asia and other places have entered the Google Lunar X PRIZE competition, which will reward the teams who complete the first commercial robotic lunar landing mission with a prize purse valued above $30 million [see "Bound for the Moon," by Michael Belfiore; SCIENTIFIC AMERICAN, April 2012].

Teams such as Moon Express and Astrobotic are already signing contracts to bring scientific payloads to the moon. These and other companies see the Lunar X PRIZE itself as just a first demonstration mission. The long-term goal is to generate a steady revenue stream from researchers and nations that do not have hundreds of millions of dollars and the technical experience to themselves land on the moon but that do have the funds to buy a single payload berth on someone else's proved lander. A $10-million ticket is still 100 times cheaper than the $1-billion government-led missions of the recent past.

Many lunar and planetary scientists are optimistic that at those prices, significantly more countries will be able to afford to send experiments to the moon, creating a second renaissance in studying the "fifth terrestrial planet" (after Earth, Mars, Mercury and Venus).

Looking beyond the moon to Mars, SpaceX is discussing the possibility of outfitting Dragon capsules originally designed to carry payloads to the ISS for carrying large ones to Mars. That would cost hundreds of millions of dollars less than recent Mars landers. If SpaceX can sell NASA or foreign space agencies on the idea, it may be able to create an inexpensive new way to carry out Mars research at just the time when space agencies across the world are struggling to afford to continue Mars exploration.

PRIVATE SPACE STATIONS

ABOUT 90 PERCENT of the 194 nations on Earth are not ISS partners and therefore do not have good prospects for substantial access to that single, large station. For nations such as China, India and South Korea, private commercial space stations may be the best bet for extended access to space for microgravity, fundamental physics, technology testing and space life sciences research, not to mention national prestige.

First and probably best known among these efforts is Bigelow Aerospace's private space station. Without much fanfare, the company has already built and is testing two prototype space stations in low Earth orbit. By providing berths for up to six researchers, Bigelow's first human-tended station will double the number of researchers in orbit at any given time. In doing that and by using private space taxis such as Boeing's planned CST-100 or SpaceX's Dragon (which are both being designed to ferry astronauts to the ISS), Bigelow's station may well be able to offer researchers, agencies and companies—both in the U.S. and abroad—quicker access to space for costs that are half or less what a Soyuz launch and ISS stay are estimated to cost.

But Bigelow is not alone in this pursuit. A second firm, called Excalibur Almaz, plans a similar but smaller station using spare Soviet-era space station modules and crew transport vehicles.

SpaceX's Dragon space capsules may also be used as long-term space stations. At present, Dragon vehicles are under contract to NASA to ferry cargo to and from the ISS. In the near future, they should also be able to fly astronauts. Yet Dragon capsules can do much more. SpaceX plans both automated and manned DragonLab missions that can fly to Earth orbit, loiter there for weeks to months as they conduct research with both internal and external payloads, and do so at a lower cost than the commercial space stations are likely to offer.

The reusable rocket revolution will make possible new kinds of science, including studies of the "ignorosphere"—too high for balloons, too low for satellites.

RETURN TO THE WILD BLACK YONDER

THESE INNOVATIONS represent the first fundamentally new ways that we have had to access space since the 1950s and 1960s, the years that suborbital research, planetary missions and Earth-orbital satellites all came of age. Yet we are still in the early stages of our budding commercial revolution, and many questions remain. How profoundly will the emerging companies change space science, how deeply will they inspire the public and how rapidly will they convince more entrepreneurs to come to the commercial space revolution? The answers depend in no small measure on how innovative researchers and space agencies can be and how quickly they learn to adapt to, and exploit, the world of commercial space to improve the ways we do space research.

Indeed, if the commercial suborbital and orbital ventures already under way succeed, they may open up another path to explore the solar system's asteroids, planets and moons. Science could benefit in much the same way it did from the private expeditions that opened up the polar regions. Why not? Such predictions are certainly one case where the sky is not the limit.

MORE TO EXPLORE

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The Commercial Spaceflight Federation: www.commercialspaceflight.org

SCIENTIFIC AMERICAN ONLINE
Watch the first private mission to the International Space Station at ScientificAmerican.com/apr2013/space

ECOLOGY

Let the Fish Breathe

In Indonesia's Raja Ampat islands, local people are leading the effort to protect the world's most diverse coral reefs—and their own livelihoods—from the ravages of overfishing

By Brendan Borrell

OUTSTANDING: Fishers in wood boats prowl Raja Ampat's teeming waters as baitfish circle a tiny island.

Brendan Borrell has reported from around the world on science and the environment and is a 2013 fellow of the Alicia Patterson Foundation.

ON A BRISK AUGUST NIGHT DORTHEUS MENTANSAN SLIPPED INTO THE CALM ocean in a wood outrigger canoe with a lantern tied to the bow. A slight, solemn man with the precise paddle stroke that comes from 30 years of practice, Dortheus counts himself as a descendant of the original clan that settled here in the Mayalibit Bay region of Indonesia's remote Raja Ampat islands. Clouds blocked the moon, but Dortheus had no trouble navigating.

Soon several grayish forms—mackerel—took shape in the lamp-lit water: darting, disappearing and reemerging. Dortheus herded the quarry to a cut in the limestone bluffs, where reddish-brown rocks formed a shallow corral. The water's surface roiled as two dozen glistening fish splashed about. Dortheus stepped into the ankle-high water with a triangular net and scooped their bodies into the canoe, where they thumped against its walls for several minutes, robotically opening and closing their mouths.

It was a ruthless method and one that few outsiders—five by Dortheus's count—had ever witnessed. The lamp seems to throw off the mackerel's sense of direction. Some villagers use the technique to catch excessive numbers of fish, but Dortheus takes only what he needs. "I'm trying to set an example," he explains. Overfishing has been "depleting the spawning zone."

In the past two years his village has prohibited fishing in a zone to the north, and the local church has ordered villagers not to fish on Saturday so that some mackerel—locally called *lema*—can breed. The actions are part of a larger effort by residents to manage natural resources and protect biodiversity. Conservationists have learned the hard way that if locals do not support top-down measures imposed on them, they may flout or overturn the regulations. In Raja Ampat's hundreds of islands, coral reefs and mangroves, conservationists have taken this idea to the extreme, helping individuals such as Dortheus take on leadership roles, design conservation programs, monitor resource use and enforce rules.

The goal of enlisting Dortheus and others is to ensure that preserving the extremely diverse Coral Triangle, which stretches from Bali to the Solomon Islands and the Philippines, does not end up harming the people who depend on its resources for food and jobs. For years conservationists set up protected areas without thinking much about how such actions would affect the human communities around them. The establishment of large, new marine protected areas, or MPAs, in Raja Ampat and the surrounding Bird's Head peninsula constitutes a crucial test case. Because community people are more involved, they are upholding the MPA rules. Yet the arrangement has also created friction among citizens who live within protected zones and others outside them who once exploited the zones for profit.

The experiment is important because under the 1992 United Nations Convention on Biological Diversity, countries have vowed to protect 10 percent of the world's marine areas by 2020, which will affect many fishing communities. The World Wildlife Fund has partnered with the State University of Papua in Indonesia to monitor villages in the Bird's Head MPAs until 2014 and possibly longer, examining how the areas influence the local people's health, economic well-being, education and cultural preservation. "Do MPAs value fish over the fishermen who depend on them?" asks Michael B. Mascia, director of social science at the World Wildlife Fund. "This is the source of conflict around the world, and there hasn't been a lot of rigorous research."

In scientific literature and publicity materials for conservation organizations, the positive social benefits of MPAs are assumed as foregone conclusions. Yet if the effects on people turn out to be negative or if people just ignore the MPA rules, then better strategies to preserve ocean health and food supplies will have to be developed immediately. The data from Bird's Head are just beginning to come in, but anecdotes are revealing some instructive insights. And the launch of this grand test is already marking a new era of accountability for marine conservation.

IN BRIEF

Marine protected areas (MPAs), which limit such activities as fishing, are increasingly popular and seem to protect fisheries and biodiversity, but little research exists on whether they help communities.

Extensive work to answer that question is now under way in Raja Ampat, a large region of hundreds of islands, coral reefs and mangroves in Indonesia.

Two lessons already seem clear: smaller reserves are more likely to benefit the local fishers because small areas are easiest to defend and are therefore more likely to flourish and to be managed sustainably. Second, the community must end up devising rules and policing compliance if MPAs are to succeed. Otherwise inhabitants may flout MPAs, and tensions can rise between locals and outsiders.

PRECEDING PAGES: DAVID DOUBILET

FISHING HOLES BECOME BATTLEGROUNDS

IN THE LATE 1990S, when Mascia was a graduate student at Duke University, the state of land conservation was light-years ahead of what was going on at sea. For example, Costa Rica had set aside 26 percent of its land in protected areas but less than 1 percent of its territorial waters. Mascia, who has degrees in biology and environmental policy, believed that more marine space needed to be protected worldwide to preserve biodiversity and to reverse the collapse of fisheries that a billion people depend on for protein. He also did not want to see conservationists and governments make the mistakes they had made on land: evicting local people from protected areas or restricting access to their resources. These top-down approaches too often harmed the world's poorest communities. The alternative—communities managing their own resources—was being heralded as a novel approach and was leading to successes involving timber production in India and water rights in South America. Sustainable practices were starting to put people first.

Translating success from land to sea requires more than getting wet. Forests can be readily marked and monitored, but economically important fish such as tuna and mackerel swim across vast distances. And isolated fishers in dugout canoes often lack the resources to prevent outsiders from zipping in with more powerful vessels and fishing technologies.

MPAs vary in tactics but generally restrict access and are zoned for different types of activities, often including no-take zones and even no-go zones. As Mascia puts it, they are about who may do what, when, where and how. But MPAs also vary in who sets the rules, who enforces them and who benefits. That variability is what led Mascia to realize that the effects on communities needed to be examined more closely, and he homed in on Raja Ampat as the place to hunt for answers.

Back in the late 1990s, Mascia surveyed 42 MPAs in the Caribbean and found that just one third of them allowed subsistence fishing and that local people rarely played a role in an MPA's management. In a recent worldwide study, he concluded that after marine reserves were established, food security remained stable or increased most of the time, which seemed like a good sign. On closer inspection, however, he realized that within a single community, some groups of fishers might be losing control of their resources as others were gaining control. The reported increases in food security were actually an illusion produced by restricting fishing rights to a subset of dominant fishers and then asking them how they were doing.

As Mascia examined such disheartening results, he started to hear more about complications at Raja Ampat, a biodiversity hotspot with a whopping 1,320 fish species and 540 coral species—about 70 percent of the global coral tally. No MPAs were in place. The region was located in the resource-rich province of West Papua, a political tinderbox that hosted indigenous tribes and a simmering separatist movement closely watched by the Indonesian military.

At about the same time, Mark Erdmann of Conservation International had noticed serious threats to the archipelago's fisheries from outsiders. Raja Ampat's original coastal inhabitants—4,000 to 5,000 people known as the Ma'ya—were once feared as headhunters but were now struggling to support their modest way of life. They had previously respected one another's traditional claims to land and fishing grounds, and they conducted seasonal closures, known as *sasi,* to manage them. Yet population pressure caused by a migration of land-based tribes to the coast and the arrival of better-equipped newcomers had turned fishing into a game of winner-takes-all.

Fishers from Sulawesi, in particular, had become notorious for the most destructive harvesting practices. Sometimes they hired locals to do the dangerous dirty work. Other times they did it themselves with the backing of the police and military. They poisoned reefs with cyanide to stun slow-growing grouper and Napoleon wrasse for the live reef-fish food trade in Hong Kong. To catch speedy fusilier fish, they flung dynamite or fertilizer bombs into the water with impunity. Then there were the trawlers. "In the old days we could catch Jack fish that were as wide as your body," says Trofinus Dailom, a 57-year-old church leader from the village of Kalitoko, who has taken part in enforcement missions around the bay. "They have been rare since the trawlers came through in the 1990s."

Raja Ampat's waters had become a battleground, and local leaders held no sway over the invaders.

RAJA AMPAT ("four kings") includes hundreds of islands around the tip of the Bird's Head peninsula at the northwestern corner of West Papua. Three protected areas already exist there (*light red*). An unusual test case is under way on the archipelago to see if community leaders can oversee four other marine protected areas (*bold*) in ways that benefit local people.

Map by Michael Newhouse

HOTSPOT: Raja Ampat, home to 70 percent of the world's coral species, could become a hub for diving instead of illegal fishing.

REINHARD DIRSCHERI *Getty Images*

TESTING THE WATERS

IN 2004 ERDMANN, an American who had been living in Indonesia off and on for 20 years, met with communities in Mayalibit Bay, the fjordlike region where Dortheus lives, to discuss how they could regain control of their resources. He could provide them with advice, training and funding to establish an MPA, but they would have to take charge. In December 2006 the traditional leaders of Raja Ampat declared their intent to create four MPAs with the help of conservation groups, and a passionate resident named Bram Goram rose to take charge of the Mayalibit MPA. Bram harnessed his knowledge of the area to expand the *sasi* system. For example, his people designate ancient cemeteries or natural features off-limits out of respect for their ancestors and believe that entering those areas, called *mon,* can lead to illness or bad luck. Bram created the hybrid concept of *sasimon* to introduce no-take zones to his neighbors. And he set up a team to patrol the waters and thus discourage infractions.

Two years later, however, residents still lacked the legal authority to prevent outsiders from exploiting their fishing grounds. That changed on March 15, 2009, when locals showed their willingness to fight for their resources. A commercial fishing boat anchored just outside the bay, along with a fleet of smaller boats, swept through the area. When Bram's patrol team confronted them, the outsiders flashed a permit from the regional fisheries office. Bram was furious and demanded that the government revoke the permit. Remarkably, the government complied and also put in place a moratorium on all outside fishing permits in Mayalibit Bay. "The community finally had the power they needed to protect their fisheries," Bram says proudly. Today 29 percent of the bay is a no-take zone, including about 40 percent of its mangroves and reefs. The other MPAs in the Bird's Head seascape developed their own protections and are in various stages of implementation.

For Mascia, these rapid changes in Raja Ampat offered a prime opportunity to examine the human impact of MPAs. An ongoing experiment in conservation could also become a test case for the social sciences. Some social scientists had conducted small-scale studies of fishing communities, but Mascia wanted to follow in the footsteps of an ambitious effort conducted on land. Arun Agrawal, a social scientist at the University of Michigan, had studied a network of 9,000 forest plots in 16 countries and found, for instance, that putting local people in charge of protecting their own forests increased forest regeneration. That finding suggested that Bram's patrols could help fish populations recover. In 2009 Mascia and his collaborator Helen Fox, also at the World Wildlife Fund, met with Agrawal to launch a monitoring program in the Coral Triangle.

In late 2010 Mascia's team began baseline surveys of 2,433 households in 102 villages inside and outside Mayalibit, Cenderawasih Bay and four other MPAs in the region. They would ask individuals, for instance, how often they went fishing or—in an effort to understand who was better off—whether they had a DVD player or a generator. The first year's data indicate that only 12 percent of households in Mayalibit face recurrent hunger, compared with 21 percent in Cenderawasih, where residents get more of their protein from sources other than seafood. Differences in how much each community relies on marine resources will impact the success of the MPA, yet it is hard to predict how. For example, locals who depend more heavily on marine resources

may be more inclined to defend them from outsiders, but they may also be prone to overexploit them. Mascia's team has finished stacks of follow-up surveys at Mayalibit and Cenderawasih and is now waiting for the data to be assessed to see if and how the areas have changed after two more years under MPA rules.

Because each protected area has its own mix of marine resources, cultural histories and levels of involvement from international conservation groups, the most important survey findings will be about the types of benefits MPAs are providing, such as food security or improved economic status. Comparing the 2010 and 2012 surveys will also elucidate contentious questions such as whether coastal farmers receive trickle-down benefits from marine protection. The team needs to study all the MPAs before drawing generalizations. For example, Mayalibit Bay is surrounded by land, which makes protecting it from outsiders somewhat straightforward. Other reserves have open water with only scattered islands, which may be more difficult to police and may mean they offer fewer benefits to the people living there.

Mascia also hopes to establish a broad repository of traditional knowledge and fishing practices throughout Raja Ampat and the Bird's Head seascape. That will help him understand the degree to which the MPA legal framework will work in concert with, or in opposition to, local leadership. The insights will help communities and policy makers improve how they are managing resources and will also help Mascia draw conclusions about who is actually benefitting from a given MPA. Conservation groups seem eager for his results; in 2011 the Society for Conservation Biology gave Mascia an Early Career Conservationist Award for the "development, mobilization and application of social scientific knowledge."

LOCAL SUCCESS IS GLOBAL SUCCESS

UNDERSTANDING THE SOCIAL IMPACTS of marine protected areas is critical as they multiply. Nearly 6,000 now exist worldwide. Ever since former president George W. Bush designated the world's largest MPA in the northwestern Hawaiian Islands in 2006, a succession of ever larger reserves have wowed conservationists but have left Mascia feeling uneasy. In April 2010, for example, the U.K. broke Bush's record with a 545,000-square-kilometer no-take reserve in the Chagos Archipelago in the Indian Ocean. The original residents of Chagos, who were evicted from the islands in 1967 and have been fighting for their return, were never consulted. To Mascia, the process of designating an MPA should not even begin until such a serious social conflict has been resolved.

Large, remote MPAs may offer countries a flashy way to meet their obligations under the Convention on Biological Diversity, but their success is tenuous. Smaller reserves are more likely to benefit subsistence fishers, who can defend the rights to their resources, giving the protected area a greater chance of long-term sustainability. Off the shore of Massachusetts or Alaska, however, industrial-scale fishing poses a very different set of challenges. Yet one lesson that can already be gleaned from Raja Ampat is that a healthy dialogue among fishers, conservationists and regulators can streamline the creation of a protected area, which is a boon for biodiversity.

Will that biodiversity be a boon for people, too? Early indications suggest that conservation in Mayalibit Bay improves the lives of the fishing community. For instance, locals used to fish intensively next to their villages, creating an ever expanding void of depleted waters. Maintaining a small conservation zone directly in front of villages has changed that. "In only two years we now see many big fish under our jetty," MPA leader Bram says. Fish allowed to take refuge in front of the village multiplied and spilled out into adjacent fishing grounds. The decision succeeded because leaders took a proactive role in managing their resources and educating their own people.

On a misty morning, I watched one gaunt villager with a canoe full of bananas pull Bram aside and tell him that he had spotted a suspicious group of outsiders in a hidden cove. The man went further, suggesting a new no-catch zone there and adding that he would like to see a monitoring outpost nearby.

"That is one of the things we want to push," Bram agreed. "Thank you," the man replied. "Some people always want to destroy our situation."

More generally, the designation of three of the four Raja Ampat MPAs—Kofiau, Misool and Dampier—has modestly reduced the harvest by outside fishers from about 99 to 90 percent, according to Crissy Huffard of Conservation International. In Mayalibit Bay, local fishers can claim nearly 60 percent of the catch, compared with 14 percent just outside the boundaries, and their patrol team has nabbed more unauthorized fishers than any other MPA.

Although conservationists dearly hope that research will show that preservation efforts are restoring marine life and enhancing local communities, they do not yet have strong proof, and they cannot say whether new forces, such as a shift in the political climate, could undermine progress. Certainly in Raja Ampat, nonnatives are not happy with the increased scrutiny, and traditional villages that fall outside of MPA boundaries complain of being left out. One worrisome development is that during my visit the local police had stopped assisting patrol teams after an officer accidentally shot and killed a fisher who was using dynamite late last year.

Funding is also a worry. Raja Ampat receives, and currently needs, substantial support from philanthropic organizations. The goal is for the MPAs to be self-sustaining via a fund collected from recreational divers who use the waters. It is too early to say whether the relationship between the local people and government will survive without international conservation groups acting as watchdogs and mediators.

And what happens if Mascia's study finds that MPAs do not help the region's fishers? "Our goal is that they are fully educated and aware of the trade-offs so that they can make their own informed decisions," Erdmann says. "That is the best we can do. In the end it is their land and natural resources, not ours." SA

MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE

Photographs and brief profiles of local Raja Ampat fishers can be found at ScientificAmerican.com/apr2013/borrell

Scientists are starting to crack the once imponderable mystery of how the big reptiles had sex

By Brian Switek

PALEONTOLOGY

LOVE AMONG THE DINOSAURS

I WAS SHUFFLING THROUGH CHICAGO'S O'HARE INTERNATIONAL AIRPORT WHEN I SAW IT: A MAGNIFICENT, towering skeleton of a dinosaur. At first I thought it was a mirage created by my travel-addled brain. But the scene did not evaporate as I approached. Pillarlike forelimbs and brawny shoulders supported a long swerve of neck bones leading up to the dinosaur's small, boxy skull, which peered over the top of a banner touting the airport's Wi-Fi, as if looking to the tarmac beyond to check the latest departures and arrivals. I stopped and stared at the behemoth—a replica of *Brachiosaurus* inherited from the Field Museum in Chicago—mentally filling in the internal organs, muscles and skin of a creature that at 85 feet long is one of the largest dinosaurs ever found. And then a strange thought bubbled up in my mind: How did such a gargantuan animal have sex?

Adapted from My Beloved Brontosaurus: On the Road with Old Bones, New Science, and Our Favorite Dinosaurs, *by Brian Switek, by arrangement with Scientific American/ Farrar, Straus and Giroux, LLC.*
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Giddy and tired, I envisioned a pair of amorous *Brachiosaurus* standing in a clearing in a conifer forest some 150 million years ago during the Jurassic period, each one waiting for the other to make the first move. But try as I might, I couldn't quite figure out the mechanics of what should come next. Could the male rear up to mount the female? Could the female support his weight? Wouldn't her massive tail get in the way? Alas, my flight started boarding, so I had to part ways with the skeleton, but I continued to ponder the

Illustration by Amy Martin

mating mystery on the plane. It has captivated me ever since.

Dinosaurs must have had sex to reproduce. As in nearly all modern-day reptiles, males would have deposited sperm inside females, which would later lay fertilized eggs containing developing dinosaur embryos. Yet although scientists have managed to deduce quite a bit about dinosaur biology, the nuts and bolts of dinosaur sex remained largely unknown—in part because studying the sexual behavior of animals was taboo historically and the topic seemed so beyond the reach of science that very little could be said about dinosaur mating with confidence. Not all hope is lost, however. Dinosaur fossils have furnished clues to such intimate details as when during development these reptiles reached sexual maturity and how they attracted mates. Meanwhile studies of birds and crocodilians—the closest living relatives of dinosaurs—hint at what the external reproductive anatomy of dinosaurs looked like. And computer modeling offers the possibility of testing theories about how these giants managed to do the deed itself. Much remains to be discovered, but scientists are slowly drawing back the curtain on dinosaur amour.

Brian Switek is a freelance science writer based in Salt Lake City. *My Beloved Brontosaurus* is his second book.

LOCK AND KEY

SIGNS OF SEX are hard to find in the fossil record of any creature. Among the rare examples are 47-million-year-old turtles that died while copulating and a pair of 320-million-year-old sharks that might have been courting when they were rapidly buried. Sadly no dinosaur skeletons have been found locked in romantic embrace. And not even the most beautifully preserved of these beasts retain remains of their reproductive organs.

For insights into the private parts of these extinct animals, scientists have had to turn to their closest extant relatives: birds and crocodilians. Birds are living dinosaurs, a specialized lineage that evolved around 150 million years ago and continues to thrive today. Crocodilians—a group that includes the alligators, gharials and crocodiles—are the closest living relatives of the group formed by extinct dinosaurs and modern birds. A trait present in both birds and crocodilians is likely to have been present in nonavian dinosaurs as well. One such trait is a cloaca—the single end point for the reproductive, urinary and intestinal tracts in both sexes of birds and crocodilians and probably, by extension, dinosaurs. Thus, an *Apatosaurus*'s genitals would not be visible as it plodded by. Instead they would have been concealed in the cloaca, which would have appeared only as a slit underneath the dinosaur's tail.

Most male birds do not have a penis inside their cloaca and instead pass semen to females by pressing their orifice to the female's in a "cloacal kiss." But some male birds are well endowed, and, intriguingly, their lineages are all near the base of the bird family tree. According to Patricia Brennan of the University of Massachusetts Amherst and her colleagues, this pattern means that ancient birds had penises and that other lineages of birds lost this trait later in their evolution. Like waterfowl and other archaic bird lineages, male crocodilians have penises, too, which they use to inseminate females in the same fashion. Thus, male dinosaurs almost certainly had them. And if the genitals of crocs and endowed birds are any indication, the dinosaur phallus took the form of a single, unpaired organ with at least one long runnel down which semen flowed during sex. That being said, with more than 1,850 genera of dinosaurs estimated to have lived between 245 million and 66 million years ago, there were probably numerous variations on this theme.

BOY OR GIRL?

RECONSTRUCTING the mating habits of dinosaurs requires more than just an understanding of their reproductive organs, however. Scientists need to be able to tell males apart from females, which in the absence of genitalia is easier said than done. Investigators have long sought skeletal characteristics that might distinguish one sex from the other in lieu of soft tissue. But most of the traits proposed to fit this bill—such as a large crest atop the head marking *Lambeosaurus* individuals as male—have turned out to be unreliable indicators of gender.

Because skeletal differences between male and female dinosaurs are so elusive, if there are any at all, the only way that we can identify dinosaur sexes is through more direct evidence. Finding developing eggs inside a dinosaur's body cavity—as with a rare oviraptorosaur specimen from China—is one way to pinpoint a female dinosaur. But there is another option. In 2000 a special specimen of *Tyrannosaurus rex* finally yielded a way to identify hidden female dinosaurs. When some species of female birds are growing eggs, they develop a thin layer of tissue called medullary bone inside the shafts of the long bones in their hind limbs. This tissue is calcium-rich and acts as a store of raw material for creating eggshells. When Mary H. Schweitzer of North Carolina State University examined the broken thighbone of the *T. rex,* she spotted medullary bone. The specimen must have been a female who was pregnant when she died. Not only did the discovery mean that this physiological response to pregnancy evolved in the dinosaur ancestors of birds, but it also revealed a means of identifying female dinosaurs—at least pregnant ones.

Building on Schweitzer's discovery, Andrew Lee, now at Midwestern University, and Sarah Werning of the University of California, Berkeley, investigated when in their development dinosaurs became sexually active. Previous work had shown that dinosaurs have rings in their bones that can be used to estimate their age at death. These so-called lines of arrested growth (or

IN BRIEF

Scientists historically skirted the subject of how dinosaurs had sex, out of modesty and an absence of evidence. **But studies** of the closest living relatives of dinosaurs are providing insights into their probable reproductive anatomy. **And computer models** can test the plausibility of putative mating positions.

SOURCE: TRACEY SWITEK

LAGs), most likely represent a yearly slowdown in growth during tough times, such as a dry season when water and food are scarce. The LAGs, along with reconstructions of dinosaur growth curves, indicate that many dinosaurs grew rapidly during their early lives and slowed as they approached skeletal maturity.

Looking at the LAGs in the pregnant *T. rex,* as well as two other dinosaurs containing traces of medullary bone—a beaked herbivore called *Tenontosaurus* and the carnivore *Allosaurus*—Lee and Werning concluded that all three dinosaurs were young moms when they died. *Tenontosaurus* perished at around eight years of age, *Allosaurus* at 10 and *Tyrannosaurus* at 18. All these dinosaurs were still growing—their skeletons had not yet developed to full maturity. And the medullary bone only indicated the latest date at which each female started having sex.

Dinosaurs lived fast and died young. Rapid growth and early reproduction, Lee and Werning suggested, might attest to difficult, dangerous lives in which mating early was required for a dinosaur to pass along its genes to the next generation. Early breeding would have been particularly important for the biggest dinosaurs. If an 80-foot dinosaur such as *Apatosaurus* took decades to grow to sexual maturity, there would be very few of them left to mate by the time they matured. Instead, Lee and Werning estimated, these dinosaurs probably started copulating long before they reached maximum size, probably by 19 years of age. Teenagers will be teenagers, after all.

BIG BANG THEORIES

BEFORE GETTING DOWN and dirty, however, dinosaurs had to attract mates. Paleontologists have wondered whether many of the extravagant adornments of dinosaurs—including crests, spikes, plates, horns and feathers—could have served to seduce. The long necks of sauropods might have functioned similarly. Although the extravagant necks most likely evolved to allow these dinosaurs to reach a wide range of food, they could have been co-opted during the mating season, possibly developing striking color patterns to advertise their good health to potential partners. (Many immense sauropods were too big to be threatened by predators and so could afford to ditch the camouflage in favor of flashy hues.) Other dinosaurs probably showed off, too. Maybe the spiky dinosaur *Kentrosaurus* found the plates and spikes of the opposite sex arousing, and perhaps females of the sauropod *Amargasaurus* looked for males with the longest neck spines. Yet for all their appeal, these extravagant traits surely complicated the act itself. Which brings us back to the question that I found myself pondering when I came across *Brachiosaurus* at O'Hare. After all the posturing and showing off, how did dinosaurs actually mate? Hypotheses for exactly how this occurred depend on what feats of strength scientists think dinosaurs were physically capable of.

Biomechanics expert R. McNeill Alexander of the University of Leeds in England imagined that dinosaurs mated just like today's elephants and rhinoceroses—females had to bear the extra weight of the mounting male. The main difference would be that dinosaurs had those big, relatively stiff tails. Working from the idea that male dinosaurs threw one of their legs over the back of the female, Alexander pointed out that the weight of the male would have rested on the female's hindquarters. This would have been a massive load, but, as Alexander noted, the resulting stresses involved would not have been any worse than those that arise from walking because, during the step cycle, the dinosaur's weight would be supported by just one hind leg as the other swung in the air during a step. "If dinosaurs were strong enough to walk, they were strong enough to copulate," Alexander wrote in 1991. "They were presumably strong enough to do both."

British paleontologist Beverly Halstead also argued that male dinosaurs had to mount the females to inseminate them. But rather than likening them to elephants and rhinos, he believed that dinosaurs did as lizards and alligators do today. Males threw one hind leg over the back of their partners, he surmised, and this move would push their hips underneath the tails of the females to bring their cloacae together. Longer-tailed species may have even intertwined their tails for more tactile stimulation, just as some snakes twist their bodies around one another.

Personally, I have never been satisfied by this standard explanation of dinosaur sex. Scientists do not really know if the legs and tails of sauropods could have bent and flexed enough to achieve the traditional position. Bipedal carnivores such as *Allosaurus* also looked like they would have required a good deal of balance and cooperation to make this kind of mating work. It is easy enough to draw a two-dimensional image of flexible dinosaurs, but no one had tested these ideas against the bones or evaluated the plausibility of other positions. Did female dinosaurs lie down on their sides during the act? Or might the lovers have backed up into each other? Researchers had no shortage of ideas but exhibited seemingly little interest in going beyond line drawings.

Extravagant traits surely complicated the act itself.

The plated, spiked stegosaurs are perhaps the most perplexing paramours of all. Consider *Kentrosaurus,* a cousin of the more famous *Stegosaurus.* This armored dinosaur sported huge spikes on its lower back and hips that must have looked dangerous to males in the mood. I asked my paleontologist friend Heinrich Mallison of the Museum of Natural History in Berlin to evaluate the possibility that *Kentrosaurus* mated in the leg-over-back position using computer models he had previously developed to study how flexible the animal was. Mallison tested dinosaur sex positions in three dimensions and concluded that the traditional dinosaur sex position did not work for *Kentrosaurus.* If a male tried to throw his leg over the back of a crouching female, he would castrate himself on her sharp spikes. One hip spike in particular seemed to be placed to strike fear in the hearts of stegosaur suitors. These prickly dinosaurs must have had sex another way—maybe the female lay down on her side, and the male reared up to rest his torso over her hindquarters. Other dinosaur species no doubt assumed different positions, which future studies may reveal. By subjecting old bones to new technologies, scientists will start to understand how the dinosaurs proliferated over their astonishing reign. SA

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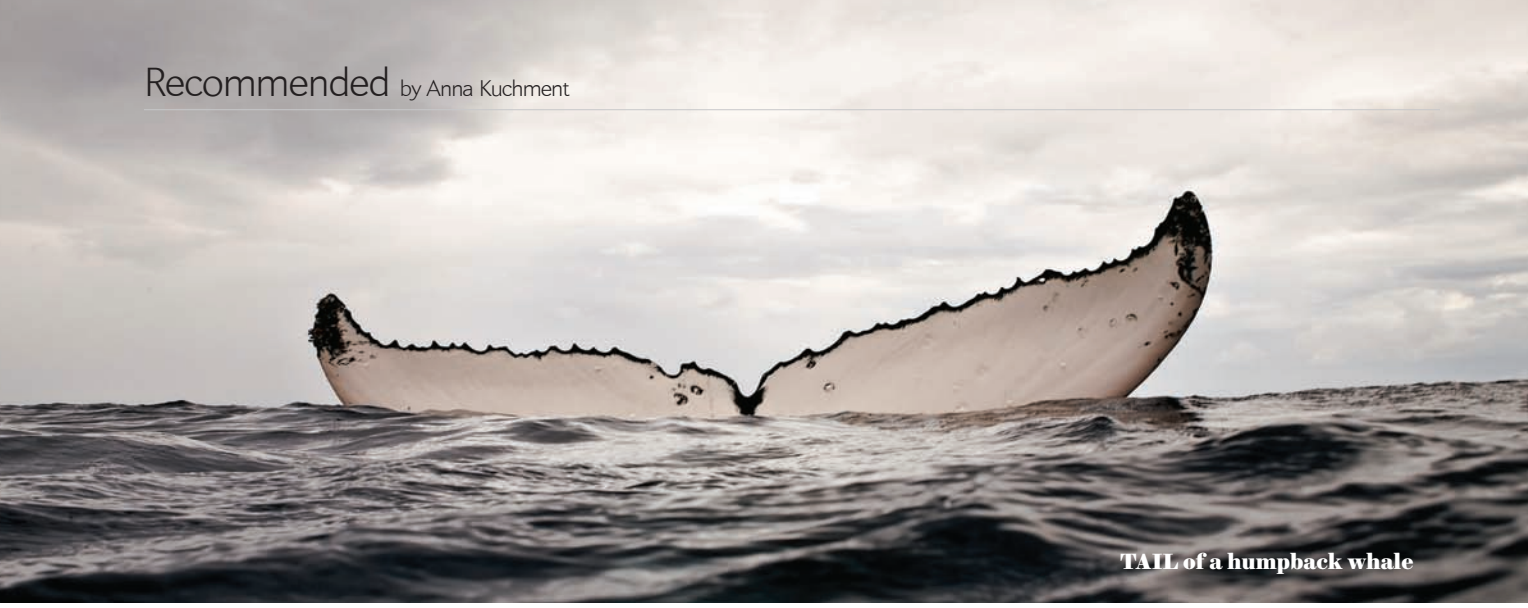
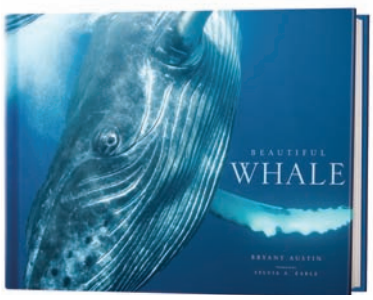
See a video on dinosaur coloration at ScientificAmerican.com/apr2013/dinosaur



TAIL of a humpback whale



Beautiful Whale

by Bryant Austin. Abrams, 2013 ($50)

Like humans, whales are "warm-blooded, air-breathing, milk-producing creatures with a little bit of hair and oversize brains," writes oceanographer Sylvia A. Earle in her introduction to this mesmerizing book of photography. Austin, who has dedicated himself to creating life-size, full-body portraits of whales, writes about his weeks and months at sea with groups of minke, humpback and sperm whales. He floats motionless in waters off Tonga, Dominica and the Great Barrier Reef until the creatures approach closely enough for him to capture them on camera.

The New Digital Age: Reshaping the Future of People, Nations and Business

by Eric Schmidt and Jared Cohen. Knopf, 2013 ($26.95)

Schmidt, executive chairman of Google, and Cohen, director of Google Ideas and a foreign policy wonk who has advised Hillary Clinton, deliver their vision of the future in this ambitious, fascinating account. For gadget geeks, the book is filled with tantalizing examples of futuristic goods and services: robotic plumbers; automated haircuts; computers that read body language; and 3-D holographs of weddings projected into the living rooms of relatives who couldn't attend. Not surprisingly, the authors are bullish on how connectivity—access to the Internet that will soon be nearly universal—will transform education, terrorism, journalism, government, privacy and war. The result, they argue, though not perfect, will be "more egalitarian, more transparent and more interesting than we can even imagine."

"We are facing a brave new world, the most fast-paced and exciting period in human history."
—Eric Schmidt and Jared Cohen

Adrenaline

by Brian B. Hoffman. Harvard University Press, 2013 ($24.95)

The first hormone ever discovered, adrenaline is associated with terror, stress and excitement and is behind animals' fight-or-flight response. Hoffman, a professor of medicine at Harvard Medical School, explores the cultural significance of adrenaline and its history. The stories include those of a murderous nurse who used the untraceable hormone to induce fatal heart attacks in her patients, industrial chemists' race to purify adrenaline for drug use and the myth of the chemical's power to raise the dead.

—Marissa Fessenden

The Book of Barely Imagined Beings: A 21st Century Bestiary

by Caspar Henderson. University of Chicago Press, 2013 ($29)

Inspired by medieval bestiaries, Henderson describes amazing but real creatures, from the axolotl (a salamander with "gills branching like soft coral from its neck") to the zebra fish (whose genetic manipulability and transparent embryos make it a good model for biology research). Each entry marries history and philosophy with science, and fantastical illustrations, photographs and diagrams enrich the book's pages. *—M.F.*

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COURTESY OF BRYANT AUSTIN *studio: cosmos*

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His book *The Believing Brain* is now out in paperback. Follow him on Twitter @michaelshermer

Proof of Hallucination

Did a neurosurgeon go to heaven?

In Eben Alexander's best-selling book *Proof of Heaven: A Neurosurgeon's Journey into the Afterlife* (Simon & Schuster), he recounts his near-death experience (NDE) during a meningitis-induced coma. When I first read that Alexander's heaven includes "a beautiful girl with high cheekbones and deep blue eyes" who offered him unconditional love, I thought, "Yeah, sure, dude. I've had that fantasy, too." Yet when I met him on the set of Larry King's new streaming-live talk show on Hulu, I realized that he genuinely believes he went to heaven. Did he?

Not likely. First, Alexander claims that his "cortex was completely shut down" and that his "near-death experience … took place not while [his] cortex was malfunctioning, but while it was simply off." In King's green room, I asked him how, if his brain was really nonfunctional, he could have any memory of these experiences, given that memories are a product of neural activity? He responded that he believes the mind can exist separately from the brain. How, where, I inquired? That we don't yet know, he rejoined. The fact that mind and consciousness are not fully explained by natural forces, however, is not proof of the supernatural. In any case, there is a reason they are called *near*-death experiences: the people who have them are not actually dead.

Second, we now know of a number of factors that produce such fantastical hallucinations, which are masterfully explained by the great neurologist Oliver Sacks in his 2012 book *Hallucinations* (Knopf). For example, Swiss neuroscientist Olaf Blanke and his colleagues produced a "shadow person" in a patient by electrically stimulating her left temporoparietal junction. "When the woman was lying down," Sacks reports, "a mild stimulation of this area gave her the impression that someone was behind her; a stronger stimulation allowed her to define the 'someone' as young but of indeterminate sex."

Sacks recalls his experience treating 80 deeply parkinsonian postencephalitic patients (as seen in the 1990 film *Awakenings,* which starred Robin Williams in a role based on Sacks), and notes, "I found that perhaps a third of them had experienced visual hallucinations for years *before* L-dopa was introduced—hallucinations of a predominantly benign and sociable sort." He speculates that "it might be related to their isolation and social deprivation, their longing for the world—an attempt to provide a virtual reality, a hallucinatory substitute for the real world which had been taken from them."

Migraine headaches also produce hallucinations, which Sacks himself has experienced as a longtime sufferer, including a "shimmering light" that was "dazzlingly bright": "It expanded, becoming an enormous arc stretching from the ground to the sky, with sharp, glittering, zigzagging borders and brilliant blue and orange colors." Compare Sacks's experience with that of Alexander's trip to heaven, where he was "in a place of clouds. Big, puffy, pink-white ones that showed up sharply against the deep blue-black sky. Higher than the clouds—immeasurably higher—flocks of transparent, shimmering beings arced across the sky, leaving long, streamerlike lines behind them."

In an article in the *Atlantic* last December, Sacks explains that the reason hallucinations seem so real "is that they deploy the very same systems in the brain that actual perceptions do. When one hallucinates voices, the auditory pathways are activated; when one hallucinates a face, the fusiform face area, normally used to perceive and identify faces in the environment, is stimulated." Sacks concludes that "the one most plausible hypothesis in Dr. Alexander's case, then, is that his NDE occurred not during his coma, but as he was surfacing from the coma and his cortex was returning to full function. It is curious that he does not allow this obvious and natural explanation, but instead insists on a supernatural one."

The reason people turn to supernatural explanations is that the mind abhors a vacuum of explanation. Because we do not yet have a fully natural explanation for mind and consciousness, people turn to supernatural explanations to fill the void. But what is more likely: That Alexander's NDE was a real trip to heaven and all these other hallucinations are the product of neural activity only? Or that all such experiences are mediated by the brain but seem real to each experiencer? To me, this evidence is proof of hallucination, not heaven. SA

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Illustration by Scott Brundage

From top: Yosemite Valley; Yellowstone Falls; and Jenny Lake at Grand Teton National Park

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Innovation and discovery as chronicled in *Scientific American*

April 1963

Continental Drift

"In 1912 Alfred Wegener proposed that the continents had originated in the breakup of one supercontinent. His idea has not been widely accepted, but new evidence suggests that the principle is correct. The range of opinion divides most sharply between the position that the earth has been rigid throughout its history, with fixed ocean basins and continents, and the idea that the earth is slightly plastic, with the continents slowly drifting over its surface, fracturing and reuniting and perhaps growing in the process. Whereas the first of these ideas has been more widely accepted, interest in continental drift is currently on the rise."

Optical Transistor

"Gallium arsenide, the crystal that has recently come into prominence for making the light-amplifying devices called lasers, has now been used to make an optical analogue of the junction transistor, a device for amplifying or switching electric signals. The advantage of the optical transistor is that light can cross the base region much faster than electrons can. To obtain high-speed (or high-frequency) operation in a conventional transistor the base must be made extremely thin to minimize signal travel time, and thinness is difficult and costly to achieve. In the optical transistor extreme thinness is unnecessary."

April 1913

Preparing for the Post-Fuel Age

"In a few centuries the world's coal mines will be exhausted. Whence shall we derive the energy to turn the wheels of industry? By harnessing nature, is the answer. Long before we took stock of our fuel supply and found that we must husband what little we have left, scientific dreamers wondered whether natural forces could not in some way be utilized. Already we are making extensive use of water power, or 'white coal' as it is called. The tide has yielded us some power and so have the waves. It is interesting to see what inventors have been doing toward the engines of the future. This issue's cover [*see illustration*] is a typical case (now being installed in Venice, Calif.), picked out at random from hundreds of patents."

Allure of the Foreign

"Hama, the Hamath of the Bible, one of the oldest cities of Syria, is situated in the valley of the Orontes, 110 English miles northeast of Damascus. The Orontes River flows through the City in the form of an S, and upon its banks are four huge water wheels, each bearing a name of its owner. They are used for pumping up the water of the Orontes for irrigation purposes, and also for supplying the

WAVE MOTOR, one of the many futuristic designs for harnessing nature, 1913

town. The largest wheel has a diameter of about 70 feet, and the Syrians declare it is the largest in existence. Like the others, it is built of wood, a dark mahogany. The axle is of iron. The creaking of the wheels is incessant day and night. They never stop."

For a photo album on the interest in foreign culture in 1913, see www.ScientificAmerican.com/apr2013/foreign-culture

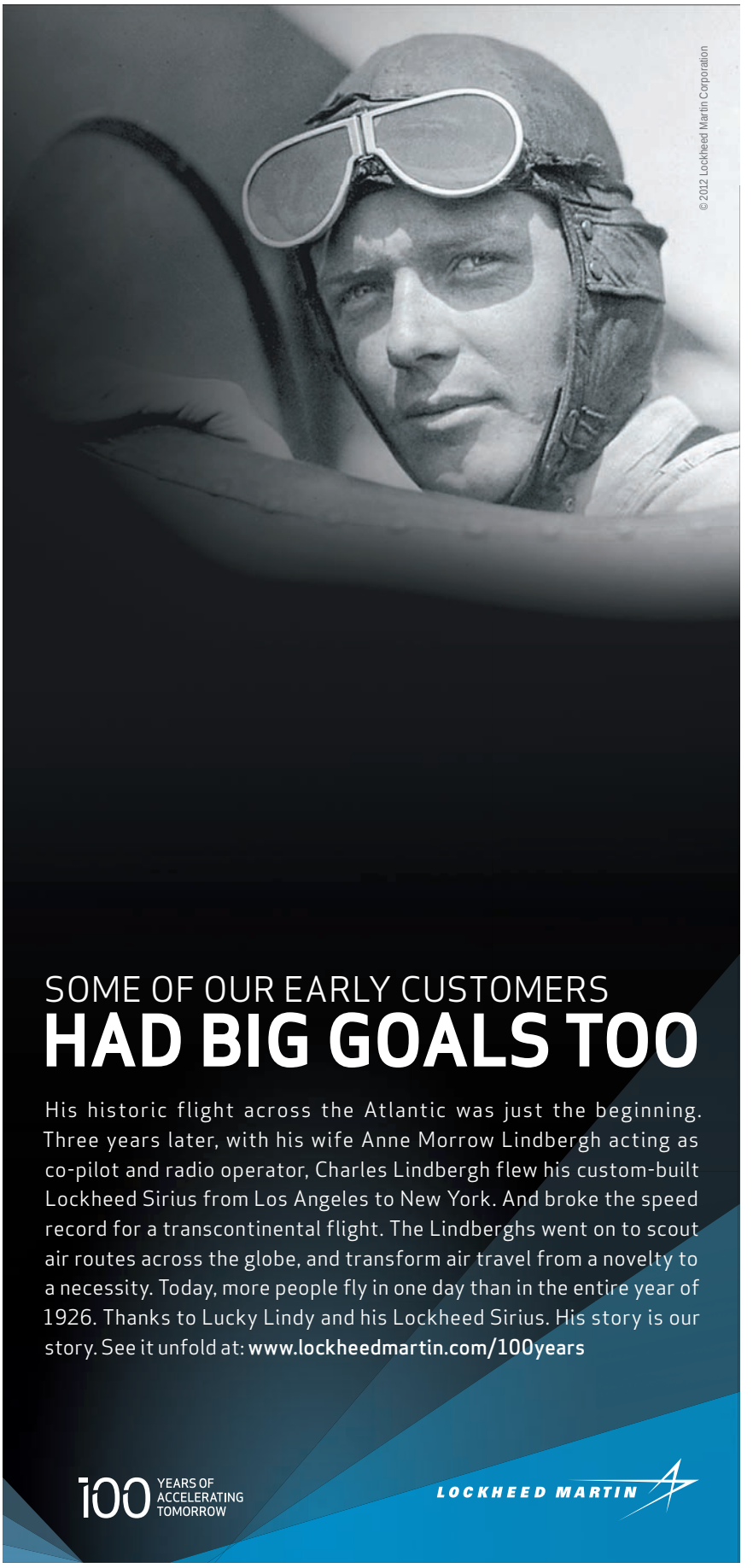
April 1863

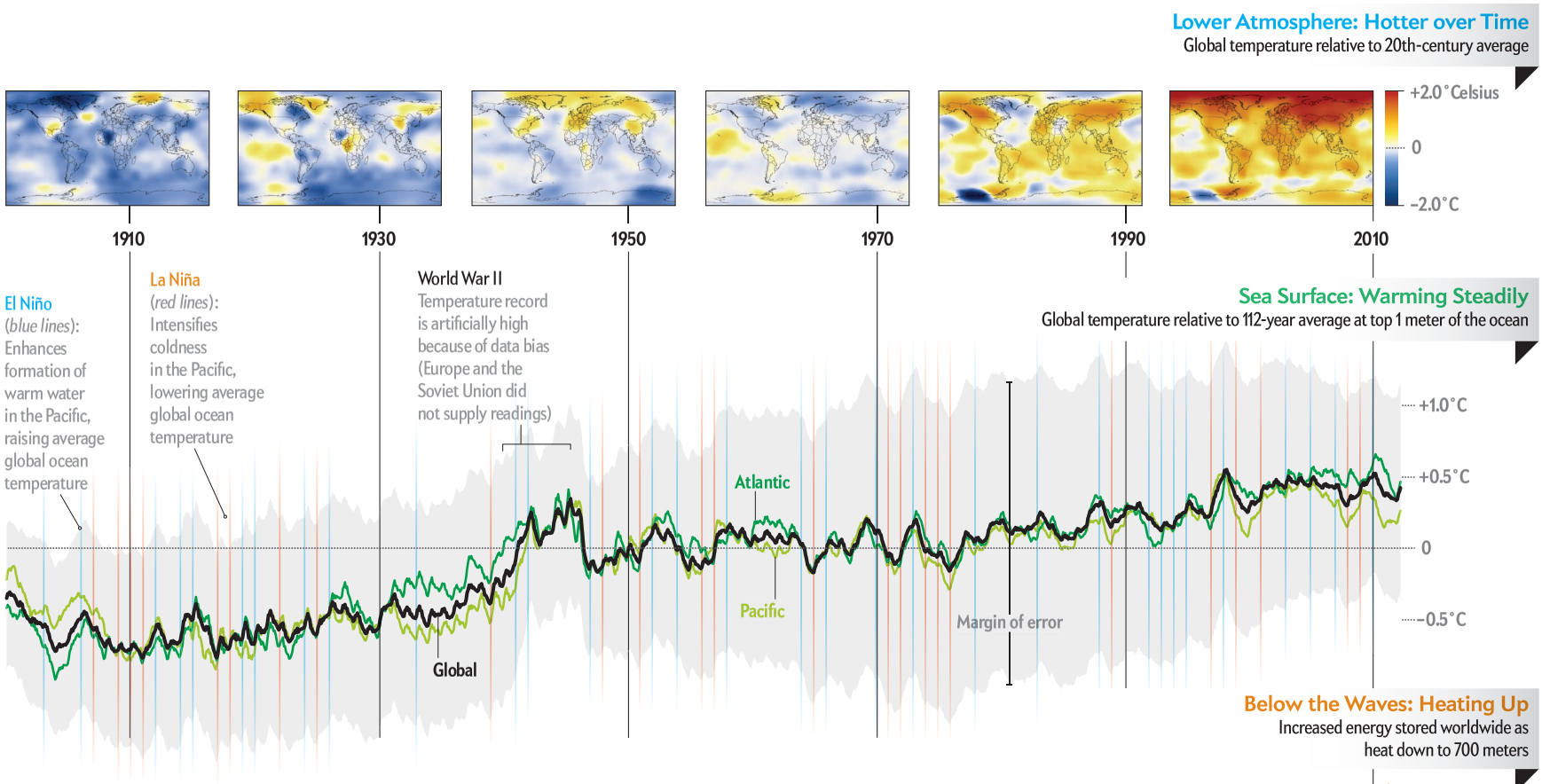
A Prairie's Value

"It is a singular fact that what were vast treeless prairies in Illinois, twelve years ago, are now covered with a dense growth of thrifty young forest trees, comprising various species of oak, hickory, cottonwood, ash, etc. So rapid has been this change in many localities, that where some of the early settlers located, twenty to twenty-five years ago, without a tree around them, they can now cut and hew good building timber a foot square. Prairie land, when kept from the annual fall burning formerly practiced by the Indians, rapidly produces a growth of trees. Some of the old citizens, who greedily located the timber land when they came to this country, and were careless about acquiring prairie, now find the latter of more value than the former; their timber has grown faster than they used it."

Japanese Paper

"Dr. McGowan, in a recent lecture on Japanese customs, exhibited an overcoat made of paper, perfectly strong and serviceable. In this country we have paper collars, but in Japan they go further and have paper handkerchiefs, which are very soft and of very fine texture. But the Japanese are more delicate than we in one respect; after they have used a handkerchief they throw it away, and are thus saved the trouble of washer women."





Deep Heat Threatens Marine Life

Warming down to 700 meters could also affect currents, weather

It stands to reason that as the atmosphere warms from the build-up of greenhouse gases, so does the ocean. Scientists have long suspected this was true, but they did not have enough solid evidence. Now they do. Data compiled by Marinexplore in Sunnyvale, Calif., not only confirm previous studies that the world's oceans are simmering, but they also bring surprising news: the heating extends beyond the first few meters of surface waters, down to 700 meters. Because most organisms live in the top 400 meters, the data suggest that warming could affect most marine life, altering food chains and migrations. It could change the distribution of life—from tiny phytoplankton to big whales—across the seven seas. "The more the atmosphere warms up, the more heat it transfers to the ocean," says Roberto De Almeida, an ocean data engineer at Marinexplore. "That heat propagates downward." Indeed, the extra energy could affect massive ocean currents and the weather patterns they influence. *—Mark Fischetti*

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See a map of ocean temperature change at ScientificAmerican.com/apr2013/graphic-science

SOURCES: MARINEXPLORE AND NOAA (*ocean data*); NASA GODDARD SPACE FLIGHT CENTER SCIENTIFIC VISUALIZATION STUDIO (*atmospheric data*)

Graphic by Jen Christiansen